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Mechanical properties of electron-beam-melted AlSi12 surface layers

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The melting parameters for an AlSi12 alloy, which lead to surface-melted layers with constant melting depth and smooth surface have been discovered using the electron beam melting technique. The main mechanical properties of the melted layer were determined with different testing methods, which were adapted for this specific use. Examination under quasistatic stresses showed an increase of the hardness of 60% compared with the base material. The tensile strength increased in the melted layer by about 50%, whereas the elongation was not reduced drastically. Examination under fatigue stress resulted in a reduced fatigue strength of the surface-melted samples. The reason for this was crack initiation at pores at the boundary of melted layer and base material. For a poreless melted AlSi12 alloy, however, the same fatigue strength as for the base material was found.

1. Introduction

The small specific thermal expansion, good mechanical properties, high hardness and good casting properties (allowing casting of complicated forms), mean that eutectic AlSi12 alloys are very often used for combustion engine parts like pistons, connecting rods and engine crank cases.

A significant disadvantage of these alloys is that the silicon crystals segregate at low solidification rates forming plates or needles between the eutectical matrix. This effect leads to an undefined reduction of the mechanical properties [1].

One possibility of improving the mechanical properties at an area close to the surface is the surface melting technique using a high energy beam, like a laser or an electron beam. Both techniques allow a local limited power supply on a surface area of 0.1 to 0.5 mm diameter with energy densities of about $10^{13}\,W\,m^{-2}$. This high energy density leads to a fast temperature rise of the metal up to the evaporation temperature. After finishing the melting procedure the melting bath cools down rapidly by thermal conduction with the cold solid metal around the melting bath. Typical cooling rates, which can be obtained with these melting techniques are 10^4 to $10^6\,K\,sec^{-1}$. These high cooling rates lead to a fine-grained structure.

Due to the high reflexion grade of aluminium alloys the workability of aluminium alloys with the laser technique is only possible with extreme expenditure, for example by covering the surface with an absorbing material. The electron beam surface melting technology is especially advantageous for aluminium alloys, as it is very efficient and prevents oxidation processes by vacuum, which is necessary for the electron beam technique. In addition, high frequency deflection of the electron beam allows a detailed dosed and controlled energy input in the surface of the material.

Some work on an improvement of the mechanical behaviour of aluminium surface layers produced by electron beam melting is reported in the literature. Lux and Hiller [2] measured the mechanical properties of an electron beam surface melted AlSi11 alloy. Samples for measuring the mechanical properties were prepared in such a way that not only an area close to the surface of at least 2 mm depth was treated, where part of the thickness was not melted, but pigs with a thickness of 7 mm were melted across the whole thickness. These pigs were used as sample material for measuring the mechanical properties by quasistatic loading. Unfortunately the fatigue strength of the surface-melted alloy is not reported.

In another publication [3], extensive examinations of the mechanical properties of a surface melted AlFe6 alloy are reported. In this work 2 mm thick sheets were treated across their whole depth.

In the following work an eutectical AlSi alloy was electron beam surface melted with 1 mm melting depth. The mechanical properties, the fatigue behaviour of the melted layer and the bonding properties of surface layer and base material were tested with different mechanical measuring procedures.

2. Surface melting procedure

The electron beam surface melting experiments were performed on 5 to 15 mm thick eutectical AlSi12 alloy sheets. The chemical composition was 11–13.5% Si, −0.3% Cu, −0.3% Mg, −0.2% Ni, balance Al. For an efficient surface melting treatment with the trace melting technique ("melting lines by lines"), which leads to small residual stresses in the layer and between layer and base material [4], it seems to be necessary to optimize the cross-section of a "melting-line" to a "rectangular form". By varying the parameters, beam current, deflection amplitude, deflection figure and deflection frequency, different

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TABLE I Optimized surface-melting parameters.

Acceleration voltage	$U = 130\,kV$
Beam current	$I = 10\,mA$
Velocity	$v = 8\,mm\,sec^{-1}$
Deflection amplitude	$a = 5\,mm$
Deflection frequency	$f = 10\,kHz$
Deflection form	Single with triangle deflection

cross-sections of a melting-line could be adjusted, such that the quality of the melted surface was influenced, thus it was possible to produce samples with a smooth surface and a nearly rectangular cross-section of the melting lines. The melting parameters given in Table I are the optimized values for the chosen melt depth of about 1 mm.

The mechanical properties of the surface melted layers were examined by different testing procedures. For these, the sample geometries were varied. The melting parameters were, however, kept constant thus resulting in a 1 mm deep melted layer, where only the melting line number and length varied for the different sample geometries.

3. Mechanical tests and results

The changed material properties of the surface-melted layers were examined by measuring the mechanical properties with static and fatigue stresses and were compared with the properties of the base material.

For a comprehensive study of the main mechanical properties of the melted surface layer the following testing methods were applied.

(i) Hardness test
(ii) Tensile test
(iii) Fatigue test
(iv) Adhesive strength test.

3.1. Hardness test

The microhardness was measured perpendicular to the surface across the whole cross-section of a melting line with the "Vickers method", thus characterizing the hardness of the melted surface layer. The testing load was 1 N for all measurements. Fig. 1 shows the hardness change of the melted layer from the surface to the base material.

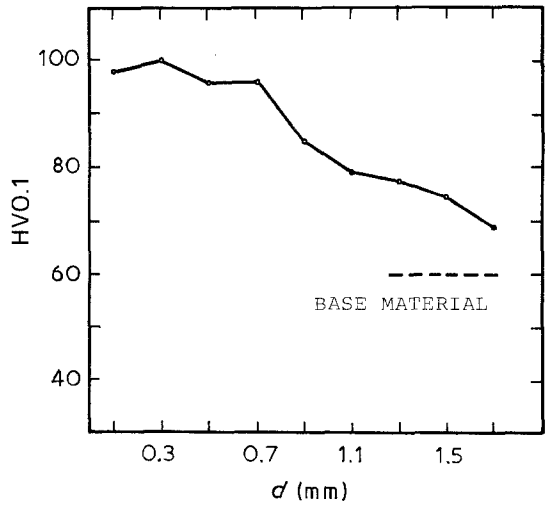

Figure 1 Hardness of the melted AlSi12 alloy plotted against melt depth. *d* is the distance from melted-layer surface.

3.2. Tensile test

Special specimens were necessary for testing tensile strength and elongation of the melted layer only. These tensile specimens were machined such that the unmelted base material was removed by milling so that the specimens consisted only of the melted layer in the tensile area (1 × 10 mm). The tensile specimens were fitted with specially designed grips in order to achieve perfect alignment. The specimens were stressed to fracture under continuously increasing tensile load. The measured tensile strength was $R_m = 305 \pm 15\,N\,mm^{-2}$ and the elongation was found to be $\varepsilon = 4 \pm 0.5\%$. Both values are mean values of three tensile tests.

3.3. Fatigue test

The fatigue properties of the melted layer were determined with an ultrasonic-resonance testing machine, which is economic in time and economic in energy. Stress frequency is about 20 kHz and constant stress amplitudes ($R = -1$) were applied in air at 20° C. More details about this machine are reported in [5] and [6].

For the measurements, surface-melted dumb-bell shaped samples (cross-section in the testing area 5 × 15 mm were stressed with the ultrasonic-resonance testing machine until cracks were initiated. By varying the applied stresses the fatigue strength and the time to fracture of the melted surface layer could be determined. For comparison the tests were performed with pure base material and with samples containing a melted surface.

In all cases the crack started from pores at the boundary of surface-melted layer and base material, which were produced during the surface treatment. Figs 2 and 3 show the crack initiation area at a pore. In Fig. 2 the crack initiation area can be recognized at the lower boundary of the pore. Fig. 3 is a higher magnification of this area, showing a fine structure with ductile facets. Fig. 4 shows the different features of fatigue fracture as well as final fracture in base and layer material (the upper part of Fig. 4 shows the layer material, the lower part shows the base material. The smooth area on the left-hand side represents the fatigue and the right-hand side the final fracture).

The final fracture is different for the melted layer and the base material. Both fracture surface parts show a dimpled structure, but the fracture of the melted layer is smoother and finer than the fracture of the base material. In contrast, no significant differences of the fracture structure are found for the fatigue failure of the melted layer and the fatigue failure of the base material.

Fig. 5 shows the results of the fatigue tests, the "Woehler" curves of base material (curve II) and electron beam treated material (curve I). The fatigue strength of the surface melted samples is lower than of the non-melted samples. This is attributed to the influence of the pores. It is not, however, possible to determine the intrinsic fatigue strength of the melted surface layer from these results as the influence of the pores is predominant. A unique relation between diameter and shape of the pores and the fatigue strength of the

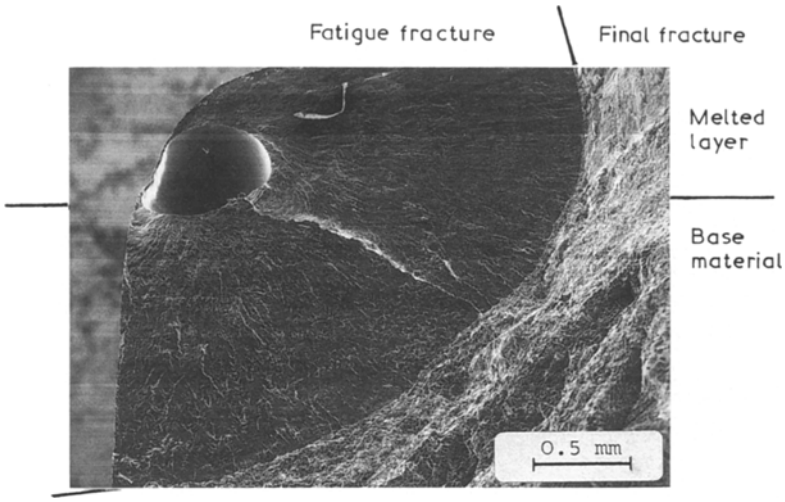

Figure 2 Fatigue fracture initiation at a pore at the boundary between melted layer and base material.

sample can be found according to the procedure of Stanzl *et al.* [7]. For smaller pores the fatigue strength increases. By extrapolation of the fatigue strength of material containing pores to these smaller pores and pore-free material, it is possible to estimate the fatigue strength of a poreless melted layer. This method reveals the fatigue strength of the surface melted layer, which is about the fatigue strength of the base material (non-melted samples). In Fig. 5 the as-determined "Woehler" curve is drawn as a broken line (curve III).

3.4. Adhesive strength test

The adhesion strength of the melted layer around the base material was determined qualitatively with a tear-off test, which seems to be a promising method also for thick ductile layers [8]. For preparation of the samples, a "sack hole" was drilled from the base material side to the melted layer. An attempt was made to tear off the layer from the base material with a stamp.

The adhesion strength of the tested AlSi12 alloy was high enough, so that the melted layer could not be separated from the base material. The stamp only sheared off the material and stamped a hole into the melted layer as shown in Fig. 6. On the upper side only, part of the layer was torn off, but not separated from the base material.

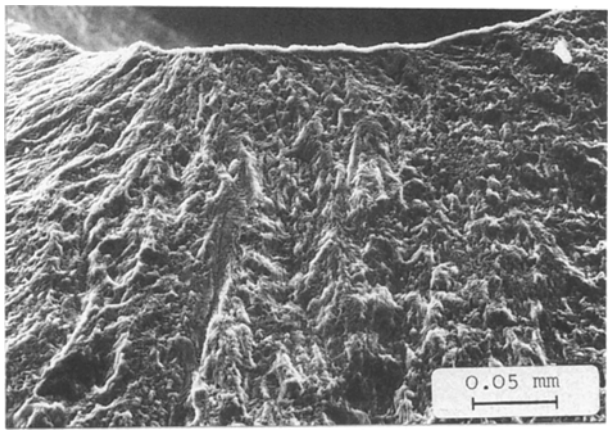

Figure 3 Higher magnification of Fig. 2, showing a part of the crack initiation area at the edge of the pore.

4. Discussion

With the "trace melting method", parallel lines with a high frequency beam deflection perpendicular to the moving direction of the workpiece, nearly rectangular cross-sections of the welds can be produced, where only an overlap of about 1.5 mm (melting-line width 5 mm) of the lines is necessary. The surfaces produced with this melting technique are smooth and free of cracks.

Other melting possibilities are for example the method producing lines without a high frequency beam deflection, and the method which melts "point by point". As the melting baths of these two melting methods are smaller, the cooling velocities are faster and lead to an improvement of the mechanical properties. This "improvement" however is accompanied by a more complex control-expenditure and often with rough surfaces containing cracks as well as a bad quality of the boundary of the melted layer and the base material.

An examination of the mechanical properties confirms the assumption that it is possible to improve the mechanical properties of an AlSi12 alloy area close to the surface by a surface melting treatment. The changed mechanical properties of the surface layers may partly be explained by the fact that hard silicon parts, which are arranged in the base material as plates and needles between the eutectic matrix, exist as finely dispersed particles in the structure of the melted layer. This microstructural change is caused by the high cooling velocity during the solidification in the electron beam treatment (about 10^4 to 10^6 K sec^{-1}).

Tensile tests revealed values of the tensile strength of 305 N mm^{-2} with a variance of $\pm$ 15 N mm^{-2}. This means an increase about 50%, whereas the elongation of the melted layer was not reduced drastically. This increase of the tensile strength is due to the grain refining process during the melting treatment.

The fractographic examination of the fracture surfaces verifies the measured results. Scanning electron microscopic photographs were taken from the tensile fracture surfaces of layer specimens. The fracture surfaces contain dimples which indicate some plastic deformation as shown in Fig. 7. Comparison with the base material yields, a finer dimple structure

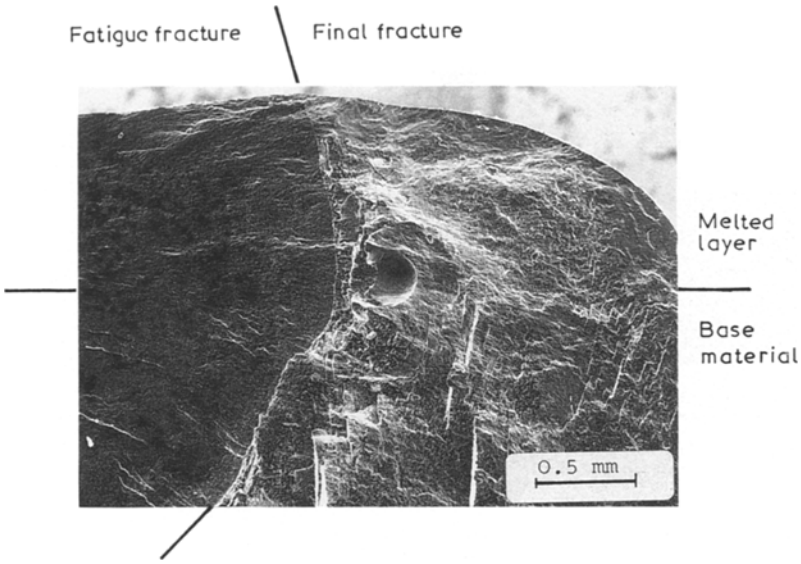

Figure 4 Fracture surface after fatigue test. Left-hand side (dark area): fatigue failure; right-hand side: final fracture; upper side (above the pore): melted layer; lower side: base material.

for the melted layer and a smaller fracture-surface roughness.

The hardness of the melted surface layer is about 60% higher than the base material. It decreases continuously from the layer to the base material and causes small stresses between melted layer and base material. The adhesion between layer and base material does not, therefore, deteriorate.

Fatigue tests showed lower fatigue strengths of surface-melted samples than of non-surface-melted samples. This decrease is caused by pores in the boundary of layer and base material, where crack initiation took place (Fig. 2). The pores may be gaseous inclusions which originate during the melting treatment. Gas is dissolved in the material and is precipitated during solidification of the melting bath. To avoid the generation of pores, it is necessary to degas the material before surface melting, or to change the melting treatment so that the melting bath is smaller. As a smaller melting bath increases the cooling velocity the diffusion length of the gas molecules will be smaller and the gas will be dissolved in the material. The other surface-melting methods discussed (lines without deflection or points by points) will be examined in future work.

Scanning electron microscope studies revealed the following differences. The final fracture of the base material is characterized by cleavage facets which are not present in the melted layer. It has to be clarified whether this cleavage fracture type is caused by the silicon plates and needles in the base material. Such cleavage facets along crystalline planes have been observed in other material with ductile behaviour [9].

The adhesion strength between the melted layer and the base material was found to be so high that the layers could not be separated. Likewise no separation of melted zone and base material took place during practical application.

5. Conclusions

Measurements of the mechanical properties have demonstrated that the electron beam surface melting technique may be very useful for high-stressed AlSi12 alloy surfaces.

(1) The increase of hardness is about 60%.

(2) The increase of the tensile strength is about 50%, with no essential reduction of the elongation.

(3) The fatigue strength of the layer is reduced compared to the base material by pores which are produced during the melting process and which are

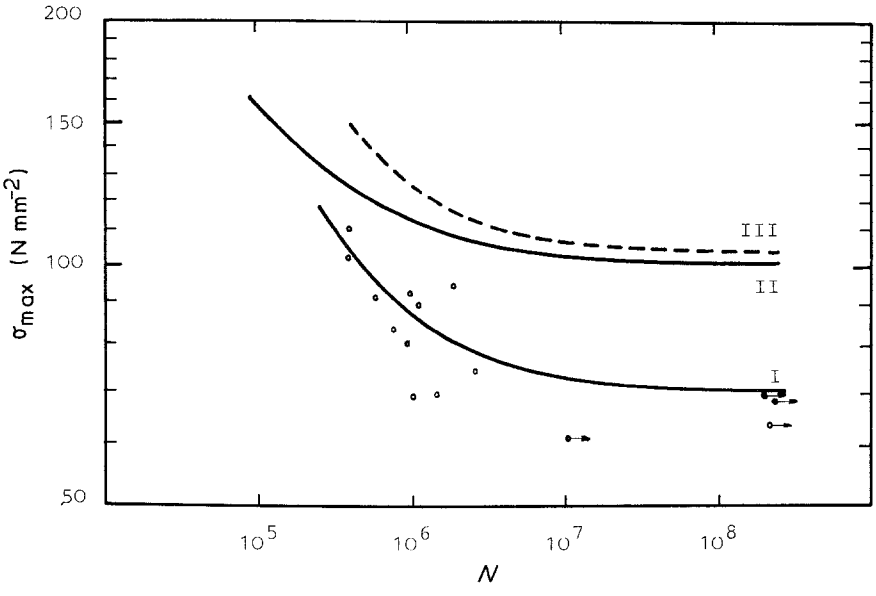

Figure 5 "Woehler" Curves of the samples with (I) one melted surface, (II) the non-melted samples and (III) the curve for a poreless melted material.

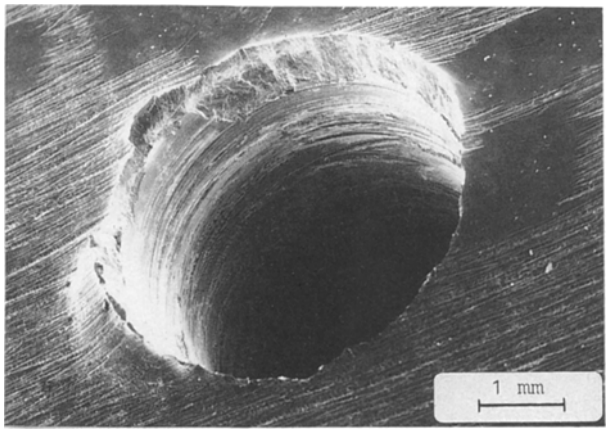

Figure 6 Sheared-off part of the surface after tear-off test.

located close to the interfaces of base material and layer. If it is possible to avoid the development of pores, the same fatigue strength of the layer as for the base material would result.

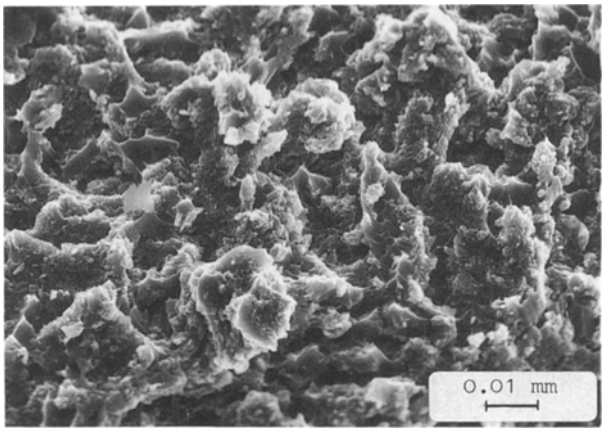

Figure 7 Fracture surface after tensile test.

(4) The adhesion strength is so high, that the layer cannot be separated.

By varying the melting parameters different melting line cross sections, melt depths and surface qualities are possible, which allows accommodation to different physical properties of the material.

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