MIG-WELDING OF MAGNESIUM ALLOYS WITH PARTICULAR CONSIDERATION OF DROP DETACHMENT

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ABSTRACT

During the last years, great progress has been made in the fields of welding power sources and filler materials for the MIG-welding of magnesium alloys. This advance resulted in a better welding process, and, therefore, in highly improved welding results. Furthermore the gap between short-circuiting- and spray-arc-transfer could be closed by the triggered short-circuiting- and the short-circuiting-arc with pulse overlay. A crucial contribution to the welding process is the energy input into the filler material. Many problems result from the physical properties of magnesium, for instance its narrow interval between melting point 600°C and vaporization point 1100°C. The energy input into the filler material has to be regulated in such a way that the wire will melt but not vaporize. For this reason, special characteristics of power sources have been examined and optimized with the help of high-speed-photographs of the welding process with particular consideration of the drop detachment. An important improvement of the weld seam profile has been achieved by using filler material of only 1.2 mm in diameter. The experiments have been made with 2.5 mm thick extruded profiles of AZ31 and AZ61. The results of tensile testing showed strength values of 80 to 100% of the base metal. Bending angles up to 60° have been reached. The fatigue strength under reversed bending of the examined magnesium alloys after welding reaches 50% of the strength of the base metal. When the seam reinforcement is ground off, the fatigue strength can be raised up to 75% of the base metal.

KEYWORDS

magnesium alloys, MIG-welding, heat input, drop detachment, fatigue behavior

1. Introduction

The importance of magnesium and magnesium alloys rises because of their potential in light weight constructions. The specific gravity of magnesium alloys, which are of technical interest, is 66% of the specific gravity of aluminum, 40% of the specific gravity of titanium and only 23% of the specific gravity of steel. In addition, magnesium alloys show a considerable strength. One can reach a reduction of weight compared with mild steel (aluminum) of about 61% (20%) considering the same stiffness (beam theory). Many manufacturers of cars try to increase the use of magnesium alloys in their products. Nowadays there are three main kinds of fabrication (die-casting, extrusion, rolling). Since there are similar problems with the welding of magnesium die-castings as there are with the arc welding of aluminum die-castings, the main emphasis lies on welding rolled and extruded products although the most parts used in magnesium alloys are die-castings. For the future the automobile industry think of magnesium alloys in space-frame-constructions as they are till now produced with aluminum alloys for example in the Audi A8 and Audi A2 [1]. One great problem has to be handled concerning a suitable joining technique for magnesium alloys, which will be a key technology [2, 3]. Besides gluing and mechanical joining methods welding is one of the most important techniques.

Welding of magnesium and its alloys is known since 1924 and was described precisely between 1929 and 1931 [4]. The earliest results concerning welding of magnesium in Germany were published 1938 and 1939 [5, 6]. During the 1960's MIG-welding of magnesium alloys required a minimum sheet thickness of 4.5 mm [7, 8]. Results about short-circuiting-, impulse- and spray-arc-welding were presented between 1960 and 1970 mainly by L.F. Lockwood from DOW Chemical Company [10-13]. Today one can find many research institutes and universities in Germany involved in gas-shielded-arc-welding of magnesium alloys [14-20]. This is because of the high interest of the industry and the new possibilities given by modern impulse-welding-power-supplies. Apart from that the problem of a high quality filler metal is solved, and therefore the basis for good welding results is given.

2. Inert-gas metal-arc welding (MIG) and drop detachment

Magnesium puts high demands on the welding process because of its physical properties. Magnesium alloys show a relatively broad melting interval of about 420-620°C, which is responsible for heat cracking. In comparison with aluminum alloys magnesium alloys have only half the vaporization temperature, that is about 1100°C. The vaporization pressure in the relevant temperature interval is 3-4 potencies higher than that of aluminum. So it is not possible to transfer the knowledge of welding aluminum alloys directly to the welding of magnesium alloys. The described effects lead to great problems concerning the heat input into the weld filler metal and therefor in the drop detachment. The weld filler must be melted but must not be overheated. Otherwise, excessive spatter formation cannot be avoided. Some problems existed concerning the quality of the filler metal, which made it nearly impossible to adjust the process with regard to the right heat input, because of the variations in diameter of about 15%. Great progress has been made since the end of 1999 by using filler metal with 1.2 mm wire diameter. This filler metal has got a very good surface and no variation in its diameter. The quality of this weld filler metal can be compared to high quality aluminum filler metal.

First experiments were welded with the help of the short-circuiting-arc. To achieve a welding-process without spatter it was necessary to use very low heat-input into the filler metal. This led to very long periods between the single short-circuits. The result were voluminous drops at the tip of the filler metal which caused problems when they reached the weld pool. Therefore a good weld-penetration could not be ensured.

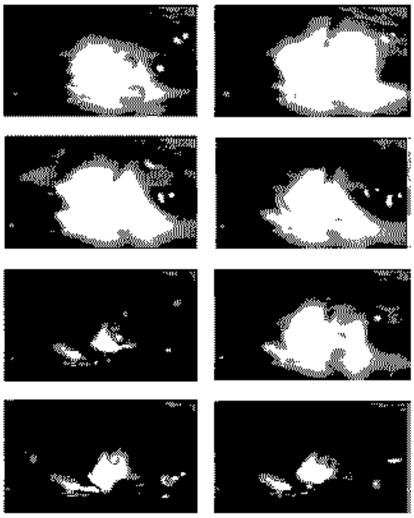

Fig. 1 Spatter-formation during MIG-impulse-welding.

For producing a better weld-penetration, impulse-arc-welding was used. But also with this technique it was not possible to increase the heat-input without getting much spatter-loss: If the energy was relatively low, it was impossible to warrant a secure drop detachment without short-circuits. The spatter-loss during some tenth of a second of the impulse-arc-welding-process (with short-circuits) is documented with the help of high-speed-photographs. Metal loss due to spatter of about 50% appeared (see figure 1). If one tried to increase the energy to avoid short-circuits, the filler metal was heated above the vaporization temperature. This let to an irregular and disturbed drop detachment because of the vaporizing filler metal which resulted again in great spatter-formation.

To reduce this spatter formation, a new welding power source characteristic (triggered short-circuiting arc) has been developed with the aid of the welding power supply manufacturer DALEX. This new welding power source characteristic has been adapted to the requirements of the material magnesium. The characteristic curve is shown in figure 2.

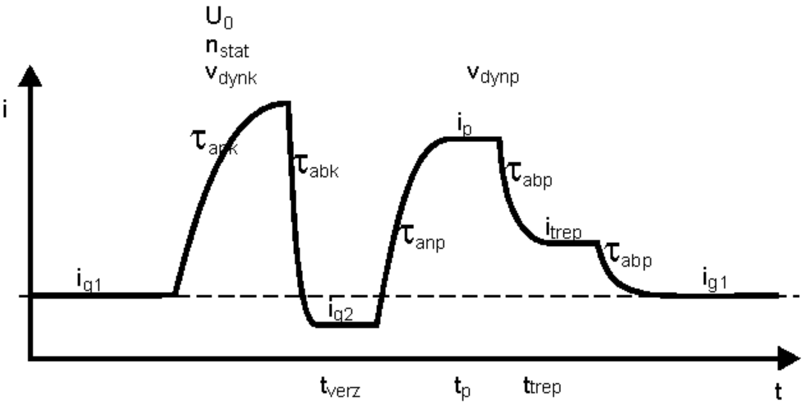

Fig. 2 Special welding power source characteristic for MIG welding of magnesium alloys (triggered short-circuiting arc).

The welding power source is based on a short-circuiting-arc-process in which the short-circuit is treated, in such a way that one can initialize the increase and decrease of the current, and thereby control the heat-input. The result is a minimum of spatter-formation. To gain a better weld-penetration a current-impulse follows the short-circuit. Consequently the characteristic curve is composed of two different sections: During the first section the heat input in the filler metal can be reduced using the parameters for a controlled short-circuit (see figure 2), resulting in defined drop detachment. The rest of the characteristic curve forms a section in which the next globule of melted metal is prepared to make it also merge softly into the melting pool shortly before the following short-circuit. Doing this, the heat input into the wire stickout is adjusted in such a way that the stickout begins to soften and is cut into. This leads to a definite volume of the globule of melted metal, necessary during the contact with the fluid pool. Consequently, the volume of melted metal merges softly into the melting pool without any metal loss due to spatter (see figure 3). The second phase cannot be limited to a specified time period. The frequency results from the succession of the short-circuits. As it can be observed in figure 4, a steady process is achieved. For this welding process, a welding power source is required, which offers the opportunity of a free programmable characteristic curve. Thus, any adjustment of the heat input into the filler metal is possible.

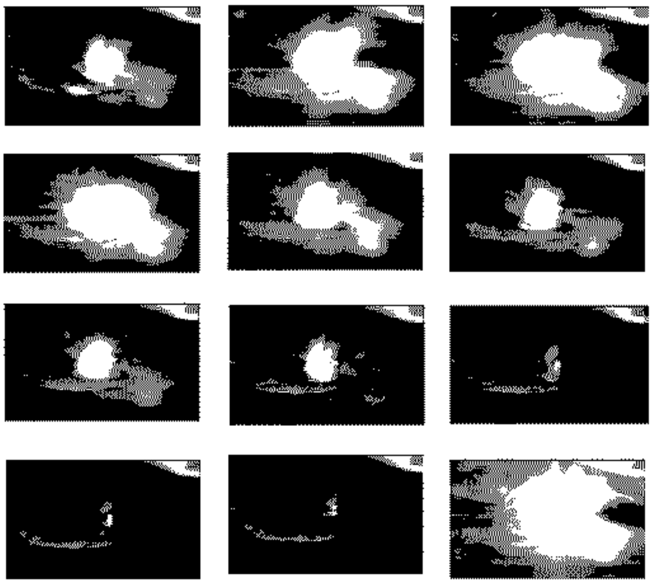

Fig. 3 Metal transfer during a triggered short-circuiting-arc.

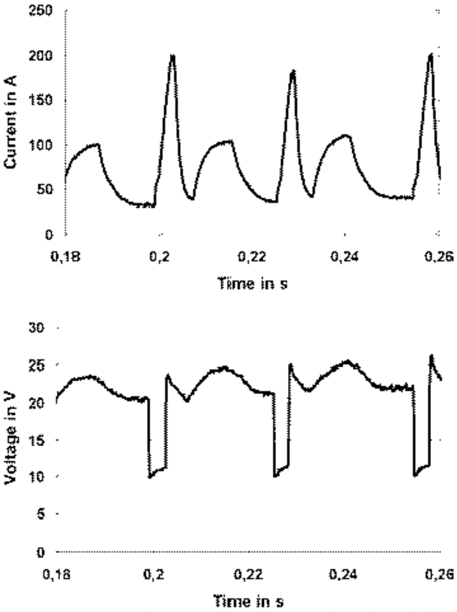

Fig. 4 Experimentally determined welding power source characteristic.

By using a high-speed camera one is able to optimize the current-voltage-characteristic and the welding parameters and therefore the drop detachment. The progress one can achieve can be seen by comparing figure 1 and 3. The reduction of spatter losses from 50% to under 1% was only possible with the help of high-speed photographs. Therewith one was able to determine the most important parameters which influence the spatter formation.

Apart from the problems that occur during the heat input, there are further difficulties concerning the transport of the magnesium filler metal, whose handling is quite problematic. These problems could be solved by using a robot-push-pull torch with planetary propulsion. This torch is able to supply the necessary constancy in propulsion for the different welding positions, which are obligatory when using a welding robot.

Furthermore, one has to consider a 10% higher thermal expansion coefficient compared to aluminum when taking into consideration the fixing of the working objects. This thermal expansion coefficient necessitates a very rigid clamping of the joining members to avoid any movement in the joining area.

With the aid of this equipment, butt welds with extruded profiles and rolled plates of 1.35 to 2.5 mm thickness have been welded. Butt weld preparation consists of gapless milled edges. Welding speed differs between 0.6 and 1.0 m/min, and wire feed speed between 6 and 8 m/min. Shielding-gas was argon with 16 l/min rate of flow. Furthermore, T-welded joints have been produced in the positions PA, PB and PD in a fully mechanized way using a welding robot (see figure 5).

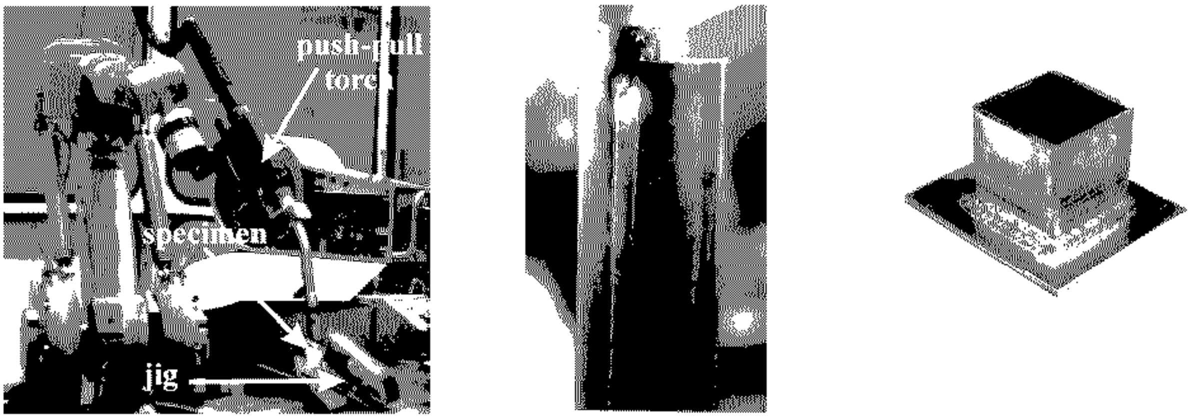

Fig. 5 Fully mechanized robotic weld of AZ31, 2.5 mm thickness, T-joints.

Further experiments were done with a prototype of a magnesium rim which consisted of two half rings (490 mm in diameter) which had to be welded together. The result is shown in figure 6.

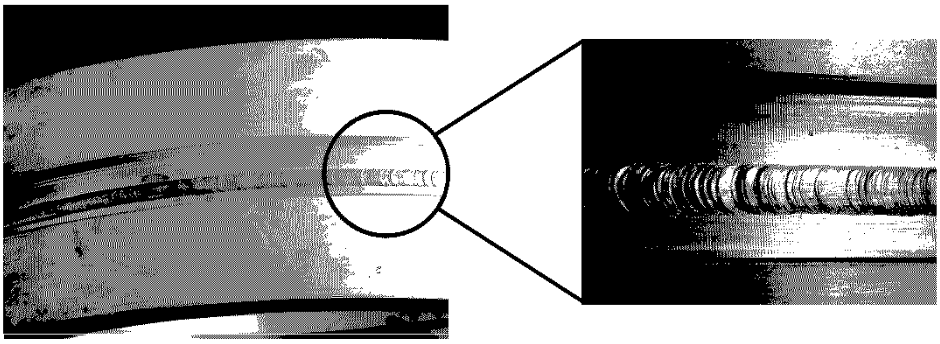

Fig. 6 MIG-welded magnesium rim consisting of two half shells.

With the help of this prototype the technical feasibility of MIG-welded magnesium structural parts could be demonstrated.

3. Metallographic investigations

In addition to the welding, metallographic investigations have been made. The structural constituents are the same as those that can be found in research papers on this subject published so far (see figure 7) [21, 22].

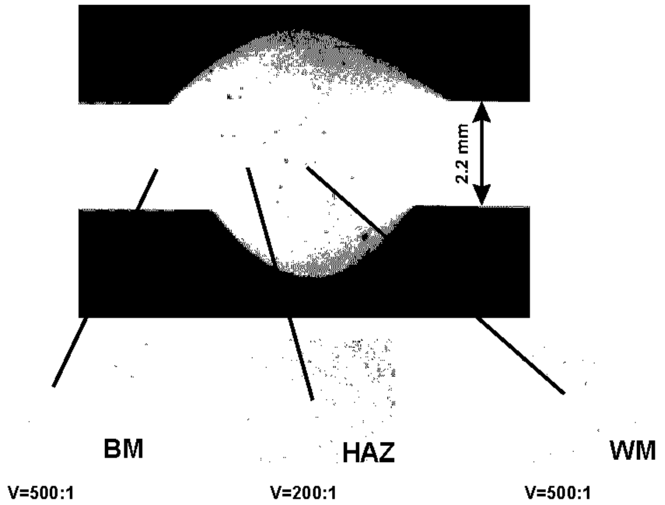

Fig. 7 Microsections of base metal, heat affected zone, weld metal of MIG-welded AZ31 with AZ61 filler metal (magnification 200 and 500 times).

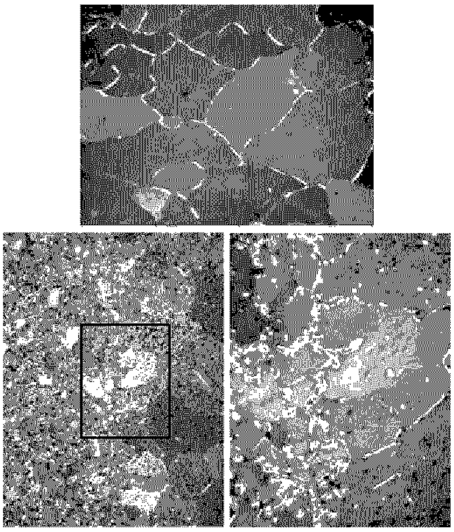

Fig. 8 Microsections (see fig. 7) using polarized light.

With the help of polarized light a welding of AZ31 with overmatched filler wire AZ61 is analyzed (see fig. 8). It is possible to show some differences between the base metal (top line) and the weld metal respectively the heat affected zone (bottom line). In the base metal the grains are coarser than in the weld metal. The grain refinement in the weld metal is one result of the higher aluminum content of the filler metal. The other effect is the higher amount of the ß-phase ($Mg_{17}Al_{12}$) in the weld metal. It is obvious, that this ß-phase is arranged on the grain-boundaries. This constellation has no negative influence on the mechanical behavior of the joints.

Mappings taken with the electron-scanning-micro-analyzer (ESMA) demonstrate the distribution of alloying elements and can help to recognize any loss of them. Analyses of welded AZ31 extruded profiles with matching (AZ31) and overmatched filler material (AZ61) show a homogenous distribution of the elements.

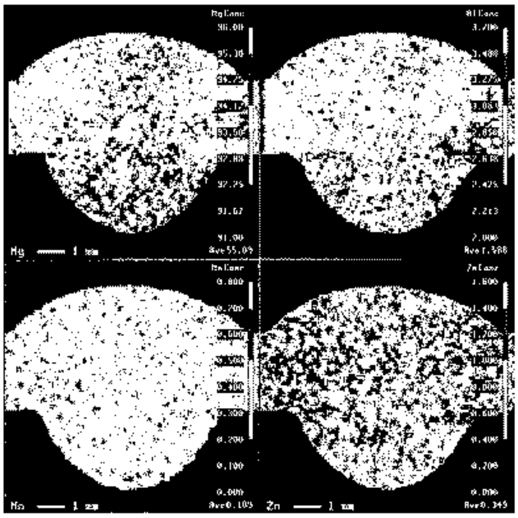

Fig. 9 Element distribution: AZ31 welded with matching filler wire, butt weld.

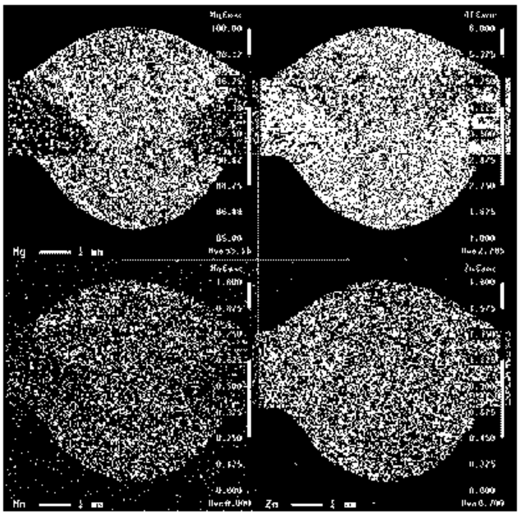

Fig. 10 Element distribution AZ31: welded with overmatched filler wire AZ61.

Differences only occur because of those between filler and base metal. Loss of alloying elements during welding can thus be excluded (see figure 9 and 10). As to be expected, the element distribution in figure 10 shows a higher content of aluminum in the welding seam. Weld deposit dilution can be determined to 50% (see figure 10).

4. Strength of MIG-welded joints

The welded joints were subjected to several mechanical tests. During the technological flexural test, bending-angles up to 60° could be reached. The evaluation of the tensile tests of the butt welds - as welded and after removal of the weld reinforcement - revealed a strength from 80 to 100% of the base metal. In figure 11 some of these results for AZ61 are shown in comparison with the specification of TIG-welded joints according to ASM. One can see that it is possible to reach nearly the strength of the base metal. In every case the specification of ASM is excelled.

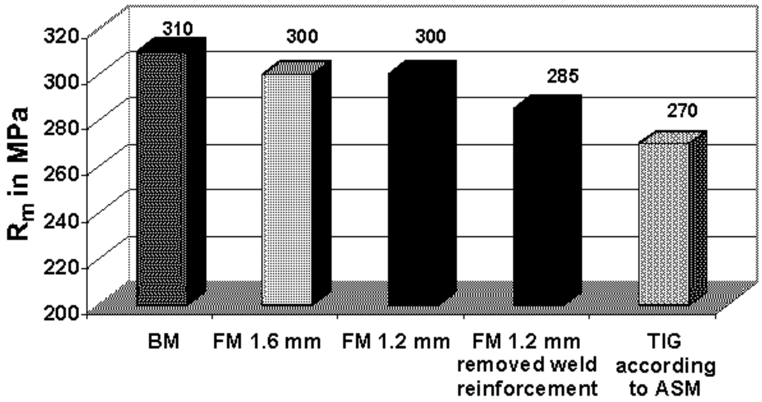

Fig. 11 Tensile tests of AZ61 (BM = base metal, FM = filler metal).

The fatigue behavior has been investigated by tests under reversed plain bending without mean-stress (R=-1). The results according to the statistical evaluation method arc-sinus-squareroot-P, relevant to the material AZ61, are shown in figure 12.

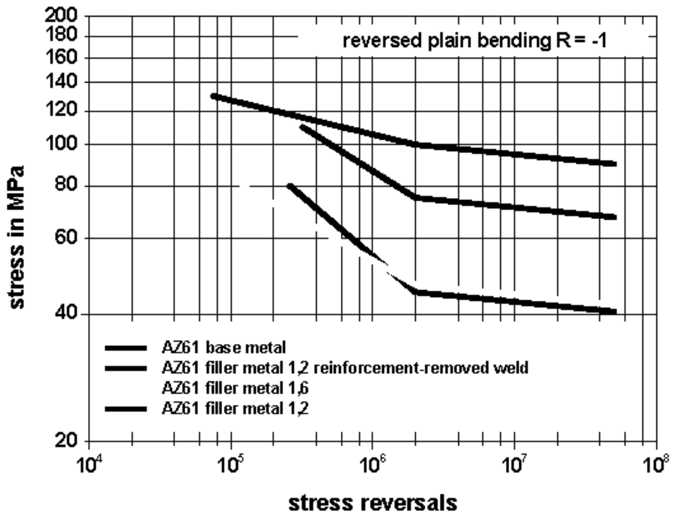

Fig. 12 S-N-curves of MIG-welded butt joints, AZ61, 2.5 mm thickness with matching filler wire, 50% probability of failure.

The fatigue strength of the as-welded joints reaches 50% of the strength of the base metal, independent of the filler wire diameter. Although the weld seam produced with the 1.2 mm filler wire shows a much smaller reinforcement and is nearly pore-free - in contrast to the one produced with a 1.6 mm filler wire -, there is no positive effect on the fatigue strength. This can be attributed to the notch effect of the root-side weld sag, which cannot be avoided. In figure 13 one can see from which position the failure starts.

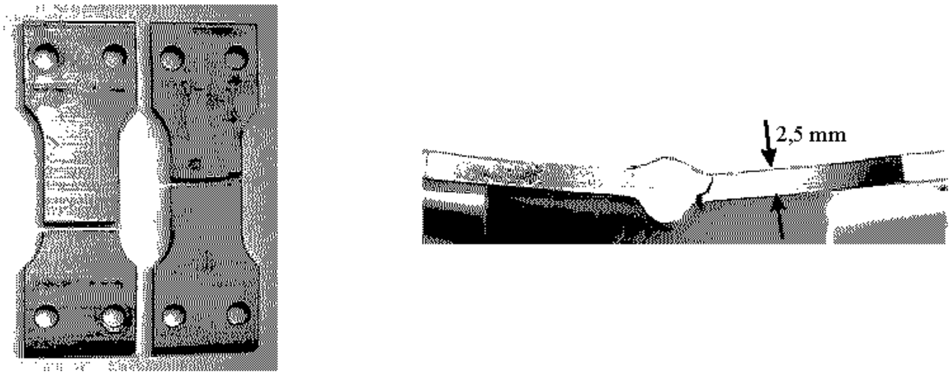

Fig. 13 Fatigue failure in the base metal (left) and crack initiation from the root (right).

On the left hand side, in the base metal, the failure starts somewhere within the measuring length. On the right hand side, the failure starts from the notch at the root-side. If the notch effect is eliminated by a removal of the weld reinforcement, the fatigue strength can be raised up to 75% of the base metal. The aim of the continuing research is to improve the weld seam profile and to increase the fatigue strength by inducing compressive residual stresses in surface layers as well.

5. Conclusion

MIG-welding of magnesium wrought alloys is possible in principle. When using a special power source characteristic the heat input into the wire stickout can be adjusted in such a way that metal loss due to spatter is avoided and a perfect drop detachment is guaranteed. The edge preparation in the welding zone has to be carried out very carefully, so that any gap is excluded. During the welding process, a rigid clamping of the joining members has to be ensured in order to avoid any movement in the joining area. The static strength of the welded joints is nearly identical with the base metal. Under cyclic loading, notches must be avoided. After removal of the seam reinforcement the fatigue strength can reach 75% of the base metal, while as-welded specimens fail at a level of 50%. The possibilities of the triggered short circuiting arc could be demonstrated with the help of a rim prototype. Fully mechanized welds using a welding robot offer new perspectives on the use of magnesium alloys, especially for sheets and extruded profiles, in the future.

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