Magnetic Pulse Welding: Joining within Microseconds – High Strength Forever

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Abstract

The commercial availability of Magnetic Pulse Welding (MPW) equipment is opening up new prospects for the technology within industrial line production. To establish MPW as a clean and safe solid state joining technology for cylindrical parts as well as sheets, comparisons to conventional fusion welding technologies are needed. The focus of this paper is on MPW-samples made of aluminum tubes (EN AW-6060) on steel or aluminum rods (C45 or EN AW-6082). They were tested in a cyclic torsion test with up to two million cycles to evaluate their fatigue strength and to compare them with the fusion welded aluminum parts of the same geometry. Even dissimilar MPW parts show an excellent performance due to the absence of critical intermetallic phases and allow for weight reduction in the powertrain. Furthermore, this work describes a possibility for energy reduction in the MPW process that allows for the downsizing of pulse generators.

Introduction

Magnetic pulse welding (MPW) is a solid state joining technology for metals [1] that is often compared with explosive welding [2], whereas a direct comparison to conventional fusion welding technologies have not been found in literature. From an end user's perspective this is of great interest in order to choose the optimal joining process for production. The focus of this study is to compare MPW and other processes on the same geometry, but with process-wise optimized joint geometry. MPW for example requires a standoff distance between flyer tube and parent part in order to accelerate the flyer through the strong magnetic pressure generated by a working coil as shown in Fig. 1. The controlled collision between two parts under a certain angle β and radial impact speeds $v_{i,r}$ is used to create a surface cleaning jet and finally the joint [2]. New publications also support the thesis of a very small melting zone [3], for example due to thermal activation of the compressed medium in the welding gap [4]. Thus intermetallic phases are reduced to an uncritical minimum making MPW favorable for dissimilar metal joining [5]. Hybrid metal joints are a promising solution to ensure lightweight parts with high strength, good electrical conductivity and gas tight joining zones. Driveshafts are one example for the class of structures mentioned first [6].

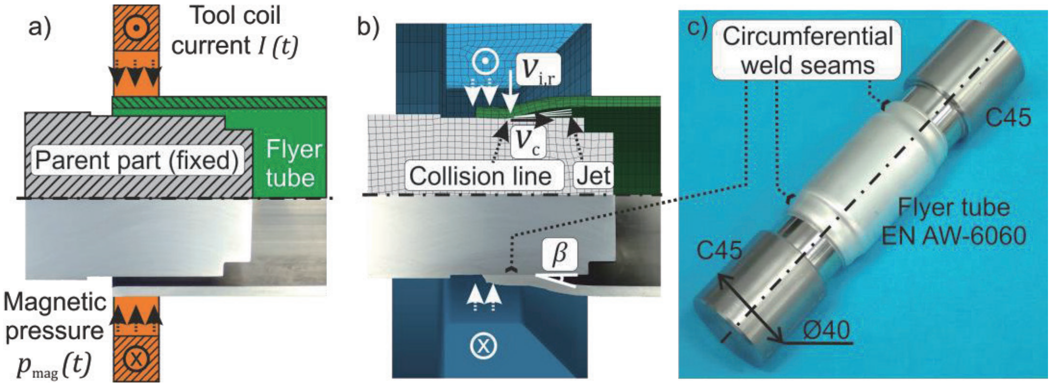


Fig. 1 MPW of tubular parts: a) magnetic pressure acts on the flyer tube's outer surface, b) time and place depended collision of accelerated flyer tube with inner parent part, c) sample with two dissimilar metal joints

In order to establish MPW as a fast and clean process in production [7], it has to be efficient as well. The MPW process can be called efficient, if the weld seam is generated with a minimum charging energy. This correlates with a minimum radial impact velocity $v_{i,r}$, if all other parameters like the electrical and mechanical properties of the flyer and the parent part as well as the welding setup are fixed. For tube welding, the minimum impact energy might be too high and deform the inner part inadmissibly [8]. In a previous publication the application of certain surface coatings during MPW were presented as another possibility for energy reduction [9].

Production of magnetic pulse welded parts

The proper welding parameters collision angle and velocity depend on various factors, for example on the part geometry and material, coil design and pulse characteristic. MPW of aluminum flyers (EN AW-6060 T4, 2 mm thickness) on steel parents (C45, normalized) are investigated in [9] and serve here as a base for the process adjustment. Finally, an optimized experimental setup designed by Bmax was used in this study with a welding gap of 1.5 mm and a slightly increased charging energy of 13.5 kJ to take the higher strength of the T66 condition into account. Weld lengths of more than two times the flyer thickness and waves with approx. 10 µm height appeared at the welding interface as shown in Fig. 2b and c. Another MPW configuration was tested to weld EN AW-6060 and EN AW-6082. Even if not optimized in term of energy, a configuration at 23 kJ was found with a different pulse generator (discharging frequency of 33.5 kHz instead of 20 kHz). Nevertheless, the maximum current amplitude was similar of around 740 kA. As a consequence of the higher impact velocity the deformation of the parent parts increased significantly (see Fig. 3c) with a maximum wave height of 140 µm. The welding time was less than 0.1 ms, so almost instantaneous. The weld qualities for both material combinations were secured by peel tests over the complete circumferences.

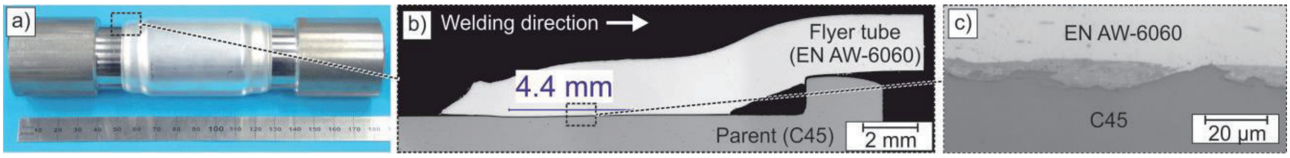


Fig. 2 a) MPW-joint between aluminum and steel, b) cross section of the welded zone with 4.4 mm weld length, c) wavy interface between aluminum and steel

For comparison reasons, two conventional fusion welding processes were used for joining the same parts; a laser beam welding process (LBW) with laser power of 1.7 kW and a welding time of 3.9 s and an electron beam welding process (EBW) with 0.83 kW and a welding time of 6.3 s. At first glance, the laser beam (6.6 kJ) and the electron beam processes (5.2 kJ) consume less energy than MPW. However, due to their lower efficiency the total energy consumption is typically three times higher for laser systems and two times higher for electron beam systems, respectively. Additionally, MPW also offers other possibilities for energy reduction. As presented in [9], an electroplated nickel layer with a thickness of 5 µm on the parent part doubles the weld length. Further experiments were conducted at the lower boundary of the welding window. It was found that the application of a nickel layer decreases the minimum collision velocity between EN AW-6060 and C45 from 350 to 230 m/s and the charging energy from 5.8 to 2.9 kJ with all other parameters being constant. The reduction of the charging energy does not only save energy but also allows for choosing a smaller pulse generator with lower investment costs for the specific joining task.

Torsion testing of welded parts

The material's strength in the magnetic pulse welded zone is normally similar or higher than the weaker base material due to hardening effects [10]. Thus components for torque transmission like driveshafts, are a promising application for magnetic pulse welded parts [6]. The main load cases for those tubular parts are static and cyclic torsion. Therefore torsion tests with simplified magnetic pulse welded driveshafts (Fig. 1c) and fusion welded samples (Fig. 3d) were conducted using a servo-hydraulic torsional testing machine from Inova. The axial force in the samples was set to zero during all tests. Each part consisted of two massive rods as parent parts (Ø40 x 70 mm) that were connected by a tube (Ø40 x 2 x 70 mm, EN AW-6060, T66). The length of the tube was reduced compared to real driveshafts to avoid buckling and assure the ability to test the weld seam. The minimum sample length was limited by the mounting ability of the rods' ends in the clamping system of the testing machine. The necessary welding gap for the flyer acceleration was machined in the rods' outer contour (Fig. 2b). Table 1 lists all tested samples configurations including the fusion welded parts used as a benchmark. For static testing, a constant angular velocity of 10 °/minute was applied while the torque was measured. Cyclic testing was performed using an alternating torque (stress ratio = -1) with constant amplitude and constant frequency of 20 Hz. The initial torque amplitude was incrementally reduced after each test, if the sample failed before 2 million stress cycles. If the sample passed, the torque amplitude was increased, respectively. With this step test method the torque amplitude for 50% probability to default was evaluated. A direct comparison of weld seam strength is difficult to obtain due to technology related differences in the geometrical seam configurations (see Table 1).

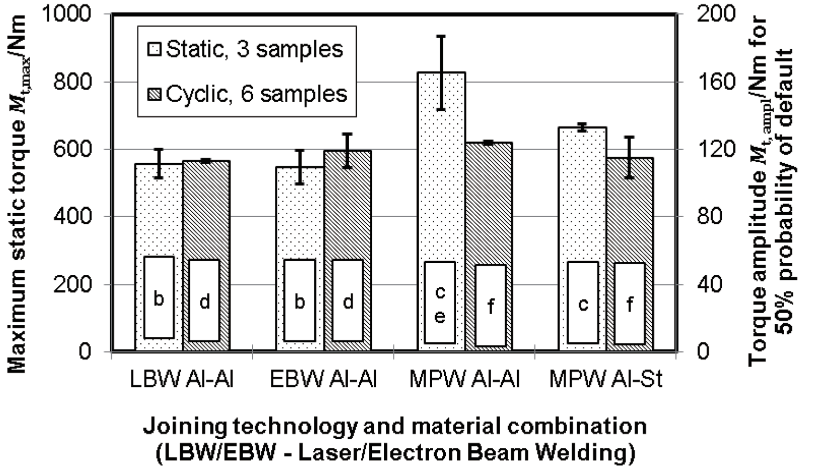
Here it is beneficial that an identical global sample geometry was chosen for all three welding technologies: a comparison is possible based on their overall torque performance.

Table 1: Sample configuration for torsion test, tube material EN AW-6060 T66

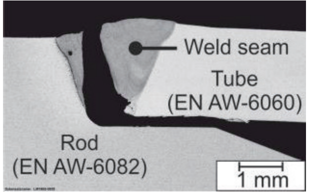
Material		**Joining**		**No. of samples**	
Rod	Tube	Technology	Joint geometry	Static	Cyclic
Al (EN AW-6082)	Al (EN AW-6060)	LBW	Butt	3	6
Al (EN AW-6082)	Al (EN AW-6060)	EBW	Butt	3	6
Al (EN AW-6082)	Al (EN AW-6060)	MPW	Overlap	3	6
St (1.0503, C45)	Al (EN AW-6060)	MPW	Overlap	3	6

Fig. 3a shows an increased static load capability until failure of the MPW samples compared to the fusion welded samples. All LBW and EBW samples failed due to a circumferential rupture next to or in the welded zone as a consequence of heat affects in the seam; see Fig. 3b. The welded zone for the MPW samples is twice as large due to the overlap geometry but without a heat affected zone. Thus the base material of the tube failed either by a circumferential rupture next to the weld or by buckling, see Fig. 3c and e, respectively. Cyclic tests revealed almost equivalent maximum torque amplitudes for all three welding technologies. Cracks appeared longitudinally in the tubes as well as radially *in* the fusion welded seams (see Fig. 3d) and radial, with some *distance*, to the MPW seam as shown in Fig. 3f. The crack propagation was not recorded during the experiments. Thus the assumption of a crack initiation in the tube and propagation towards the weld seam has to be verified in further experiments.

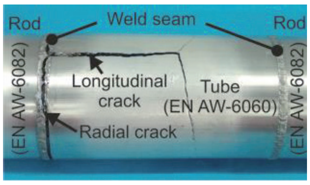
a) Static and cyclic torque capability of Ø40 mm samples (see Fig. 1c)



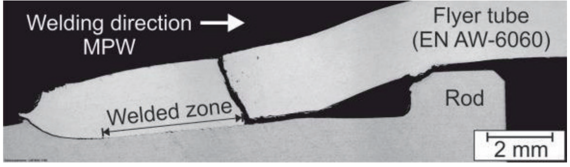
b) Circumferential rupture next to LBW/EBW weld seam or within (cross section)



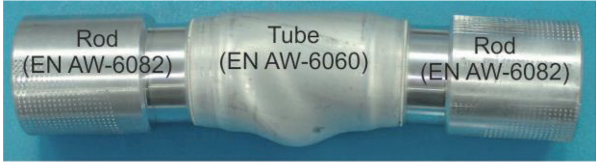
d) Longitudinal cracks in tube, radial cracks in LBW/EBW weld seam



c) Circumferential rupture next to welded zone in the tube (exemplary cross section with EN AW-6082 rod)



e) Buckling of the tube



f) Longitudinal cracks in the tube and radial cracks next to welded zone (exemplary cross section with C45 rod)

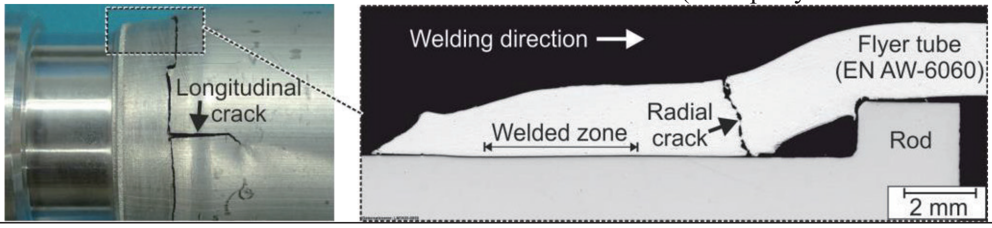


Fig. 3 a) Static and cyclic torque capability with similar and dissimilar material combinations and different welding technologies b)-f) indication of failure mode

The enlargement of the sample number would have been also necessary for statistical cross checking. Nevertheless it can be stated that, in contrast to fusion welding technologies, MPW offers also the possibility of dissimilar metal joining. This is shown for the combination of steel and aluminum in Fig. 2c. Due to the low heat input no critical intermetallic phases are formed and thus the applicability of lightweight mixed material parts joined by MPW is proven in Fig. 3a.

Conclusions

Within this study, the production process of magnetic pulse welded samples was characterized and compared with fusion welded parts of the same geometry, but with process-wise optimized joint geometries. Samples generated with MPW, LBW and EBW were tested under static and dynamic torsion load and directly compared with each other. Three statements regarding MPW can be formulated:

I. Compared to fusion welded parts the capability for static torsion loads is higher due to the process specific overlap welding configuration and the absence of heat affected zones. Fatigue tests show similar maximum load amplitudes for all three investigated processes, probably due to crack initiation in the base material of the tube.
II. In contrast to fusion based processes, MPW can join dissimilar metals like steel and aluminum enabling lightweight design with excellent load bearing capabilities.
III. Electroplated nickel coatings on the parent part allow for energy reduction during MPW of aluminum on steel and thus downsizing of pulse generators.

For future investigations it is planned to analyze the crack propagation in detail. Furthermore, an economical comparison of the welding technologies will be carried out, including the weight saving potentials of dissimilar MPW joints.

Acknowledgments

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