FRICTION STIR WELDING IN THE AUTOMOTIVE INDUSTRY

Christopher B. Smith, Wade Crusan, Jonathan R. Hootman,
John F. Hinrichs, Robert. J. Heideman, and Jeffrey S. Noruk

Tower Automotive – Technology Application
3533 N. 27th St.
Milwaukee WI, 53216

Abstract

As the automotive industry trends towards increased use of aluminum, the friction stir welding (FSW) process offers many potential benefits for joining of aluminum. In contrast to most other joining processes, FSW is a more robust process, being more capable of handling the variations inherent in high volume production. FSW also provides for improved mechanical properties, as compared to other joining processes. However, FSW requires significant process forces. In the initial stages of development, FSW had unacceptably low travel speeds. This paper will describe applications for the FSW process in the automotive industry, as well as suitable friction stir welding equipment. In addition, there will be discussion of the process limitations and how they have been overcome to make FSW a very robust process for the automotive industry.

Introduction

With FSW having many advantages, including improved mechanical properties (tensile and fatigue), improved process robustness, lack of consumables, less health and environmental issues, and operating cost advantages, it has gained significant interest in the automotive indusry[1,2]. To-date, the interest and application of FSW in the automotive industry has been in three general categories. These three categories include the joining of extrusions to form "larger extrusions," joining of tailor welded blanks, and joining for various assembly applications. FSW in each of these categories has distinct benefits and resulting cost reductions and/or other advantages that allow its application to be beneficial. Each of these categories will be discussed in more detail.

For each of these categories, joint design is an important consideration. For the joining of extrusions and general assembly applications, there are two basic joint configurations that will likely be employed. These two joint designs are the partial penetration butt weld and the lap weld, as these are the most capable of handling process variations inherent in high volume production. However, the tailor welded blank requires a full penetration butt weld, but production variations are less significant in this application, allowing FSW of tailor welded blanks to be feasible.

In all of these applications, the travel speeds of FSW originally would have been too slow to economically justify the use of FSW. However, through extensive process development efforts the travel speeds have improved, and as such, is not an issue anymore.

Applications

Joining of Extrusions

The joining of extrusions with the use of FSW is regarded as an enabling technology to generate larger extrusions profiles, which could not be previously fabricated. For the automotive industry, it is generally accepted that the largest available extrusions are in the 200 mm to 300 mm diameter range. Larger extrusions can be fabricated, but their cost per mass of material increases with increasing extrusion size. Furthermore, the extrusion tolerances become worse as their size increases, often making them unusable.

With FSW, two smaller extrusions can be joined with various weld joint configurations to generate larger extrusions. In this application, the friction stir welds are linear welds, as long as the extrusions, themselves. Once welded, the "large" extrusion often enters a sawing operation, where the extrusion is cut into a smaller section. One such example is a patent pending suspension component shown in Figure 1. This particular part is a suspension link arm, and was cut from several meter long welded sections. For this application, the partial penetration butt weld configuration would be most appropriate, though lap penetration, lap fillet, or full penetration butt weld configurations can also be used.

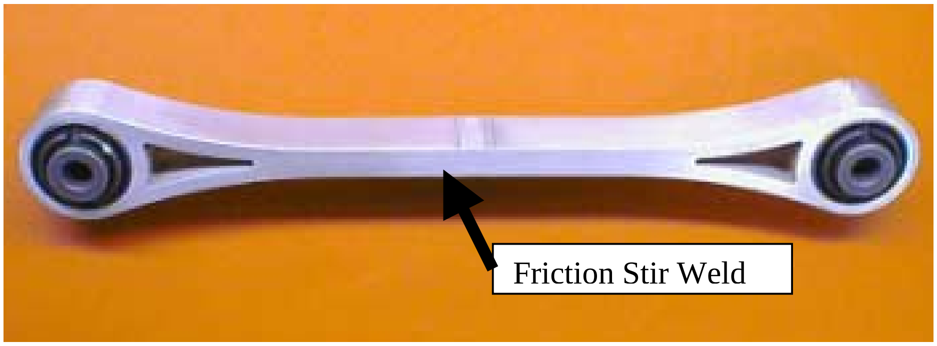

Figure 1: Automotive Link Arm Fabricated from Friction Stir Welded Extrusions

This FSW application requires a custom linear machine, due to the length of the weld, the required travel speeds to make this process cost competitive, and the associated process forces. The capital cost of these machines is quite significant. However, due to the use of lower cost extrusions (cost/mass), a lower net-cost extrusion can often be generated. In this application, travel speed is a critical factor in the net cost of the process, as the largest cost associated with the operation is the capital cost of the machine, since there are generally no consumables with the FSW process resulting in minimal operating cost. An example of a custom production machine (manufactured by ESAB AB of Laxa, Sweden) is shown in Figure 2. This particular machine will be used for a production automotive link arm similar to that illustrated in Figure 1.

Figure 2: ESAB Production FSW Machine

General Assembly

The general assembly application involves the joining of various components as one of the operations to fabricate an assembly. These welds will typically be relatively short (less than a meter) and can have three-dimensional contours. In the high volume production environment, the joint configuration for this type of application must be robust to variations in parts. These variations can consist of material thickness variations and other variations that cause gap conditions. For this reason, it is likely that joint configurations will be limited to lap welds (lap penetration and lap fillet) or partial penetration butt welds. These joint configurations are displayed in Figure 3.

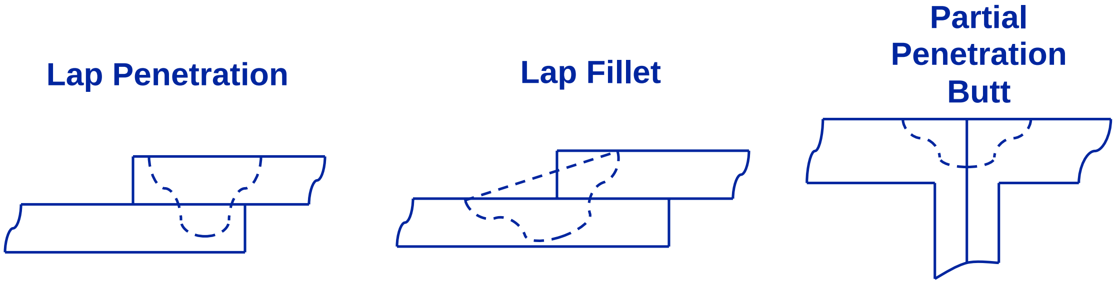

Figure 3: Lap Penetration, Lap Fillet, and Partial Penetration Butt Weld Joint Configurations (Friction Stir Weld Nugget Indicated by Dashed Lines)

Since it is anticipated that applications of this sort will often involve three-dimensional paths, a machine with at least five degrees of freedom will be necessary. When considering the need for five degrees of freedom and cost sensitivity in the automotive industry, it will be desirable to utilize industrial robots for this application.

However, typical industrial robots lack stiffness and are questionable as their ability to perform FSW. However, work at Tower Automotive, has shown that a low cost standard industrial robot (ABB IRB 6400) can perform FSW[3,4,5,6.] This robot has been able to make welds in 6061-T6 aluminum in thicknesses up to 4 mm at travel speeds of 1 m / min. With lower material thicknesses, even greater travel speeds have been achieved. The enabling technology for this robot to perform FSW is its open architecture, which has allowed the development of a force control algorithm that in-turn, allows the robot to overcome its stiffness limitation. This system is shown in Figure 4. However, for the standard industrial robot to be accepted as a high volume production capable machine, some increase in stiffness will still likely be necessary.

Figure 4: FSW System Integrated to a Standard Industrial Robot.

Other research has shown that a NEOS Tricept Robot is capable of performing FSW[7]. This robot is considerably stiffer than a standard industrial robot, due to its parallel arm configuration. However, the robot is significantly more costly. FSW research on this robot has also indicated that force control extends the capability of this robot, as well. Figure 5 displays this robot.

Figure 5: Neos Tricept Robot

Tailor Welded Blanks

Another major potential application area for friction stir welding is the tailor welded blank (TWB). The TWB consists of various sections of flat sheet, which are abutted and then joined together. These joined flat sheets then enter a forming operation to shape the joined sheets into their final geometry. The purpose of the TWB is to optimize material utilization, not only for improved material utilization, but also for reducing the weight of the final formed component. These tailor welded blanks often have variations in material thickness across the joint line. To join the blanks that have variations in material thickness, a dissimilar thickness butt weld is required.

Figure 6: Tailor Welded Blank

Research has indicated that welding from the step side (resulting weld shown in Figure 7) of the joint produces far superior mechanical properties[8,9,10]. However, this requires the FSW machine have five degrees of freedom, as non-zero work and travel angles are required for this application. The work and travel angles are described and shown in Figure 8.

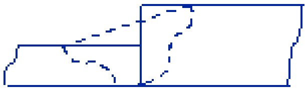

Figure 7: Friction Stir Weld of a Tailor Welded Blank from the Stepped Side

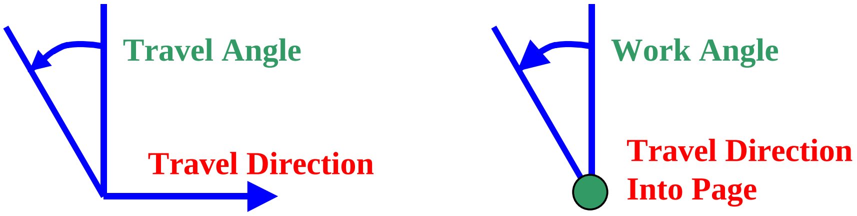

Figure 8: Travel and Work Angle Definition

Since this application requires a machine possessing at least five degrees of freedom, a robot is required. In the automotive industry, tailor welded blanks will likely be in the thickness range that a standard industrial robot is capable of welding. In fact, the robotic system shown in Figure 4 has been used to generate numerous tailor welded blank samples[3,8].

Joint Configurations

Lap Penetration Weld

During early development of the FSW process, it was believed that the lap penetration joint would be more favorable than a full penetration butt joint. In the automotive industry, the high volume production would make it extremely difficult to control tolerances that are required for full penetration butt welds. The use of the full penetration butt weld configuration is perceived to be less favorable because of its sensitivity to lack of full penetration. Penetration depth is controlled only by the FSW tool's pin length, which is constant, unless an adjustable pin length tool is employed. If significant material thickness variations occur, poor quality welds will result.

Early research indicated that the lap penetration weld also had potential quality issues. This research indicated that a certain defect, referred to as "interface deformation," was present in lap welds when tools with the original tool design geometries were used. Original lap welding work was done with tools designed for butt welds, which was the tool geometry with which the process was originally developed[11,12]. The interface deformation created by this tool design led to low tensile results of lap welds, due to the effective reduction in thickness of the upper or lower plate (dependant on direction of interface deformation). A weld showing significant interface deformation is shown in Figure 9. This defect is related to undesirable material flows within the weld nugget, with material being forced in the vertical direction on the outside of the tool's pin.

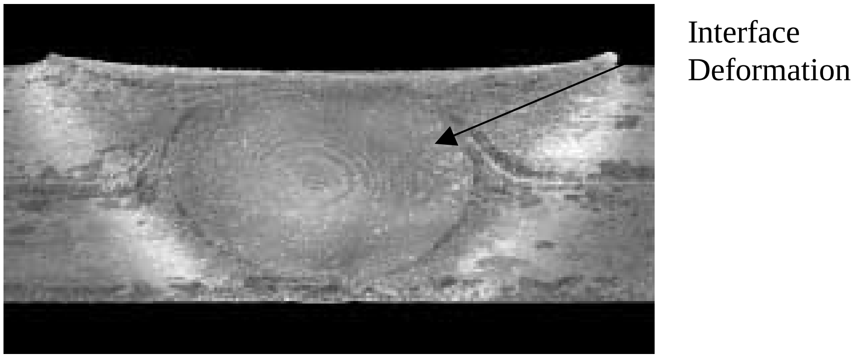

Figure 9: Lap Penetration Weld (3 mm to 3 mm 6061-T6) Displaying Interface Deformation

The source of this problem is too much material flow in the vertical direction. To reduce the vertical flow and thus eliminate this feature, a new tool design was invented and patented[13]. A typical weld with this patented tool is shown in Figure 10.

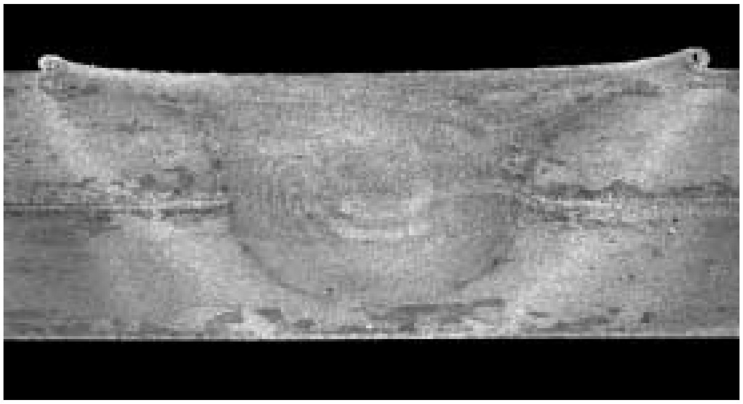

Figure 10: Lap Penetration Weld (3mm to 3 mm 6061-T6) Made with the Tower Automotive Lap Weld Tool

This tool has shown that much improved lap weld mechanical properties can be generated with it[12] with joint efficiencies ranging from 50 to 70%. In addition, welds with much improved fatigue life as compared to welds made with the original tool design can be made. Figure 11 shows a SN curve displaying the fatigue life (R-ratio < 0.1) of lap penetration welds made with the original tool design, the Tower Lap Weld Tool design, and also, as a comparison, gas metal arc welds in a similar joint configuration. In all cases, 3 mm to 3 mm lap welds were made in 6061-T6.

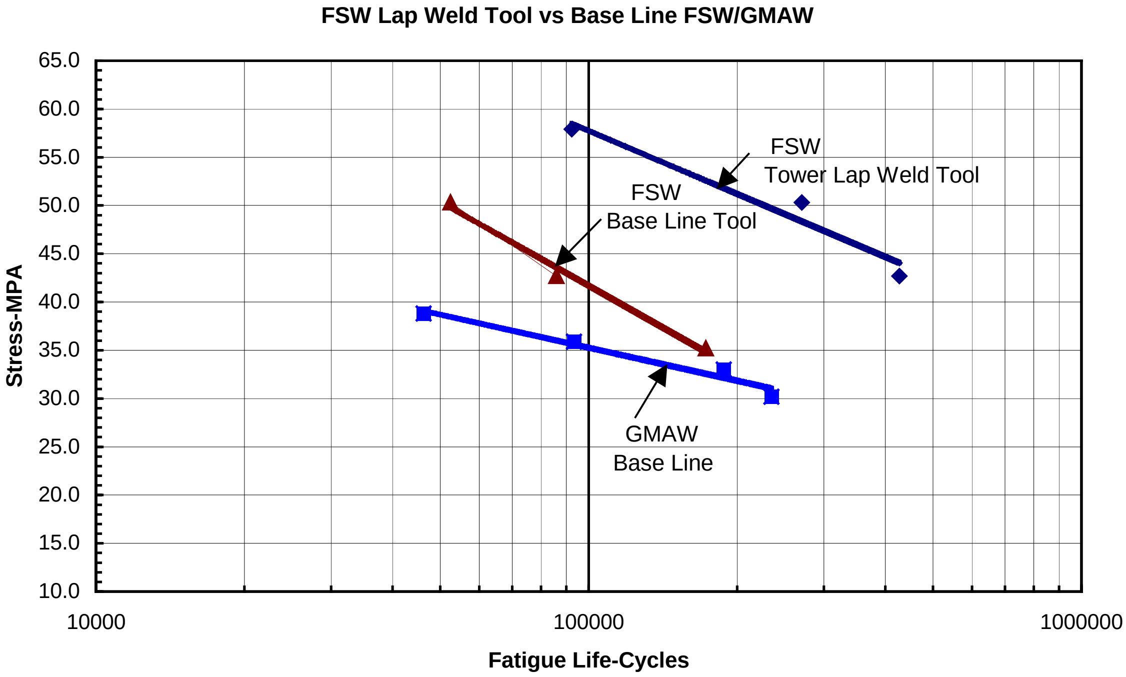

Figure 11: Fatigue Life of FSW Lap Penetration Welds and Gas Metal Arc Welds (3 mm to 3mm 6061-T6)

Partial Penetration Butt Weld

As previously indicated, a full penetration butt weld is not likely to be a successful joint configuration in the automotive industry, due to material thickness variations that are inherent with high volume assembly. The full penetration butt weld typically requires a penetration depth between 0.1 mm and 0.2 mm less than the full thickness of the weld, giving a 0.1 mm window on penetration depth with respect to material thickness. This is almost impossible to maintain without pre-machining of weld joint. Pre-machining of a weld joint adds significantly to the cost and is considered unacceptable in high volume production. An alternative to this approach is to implement the partial penetration butt weld. With this weld, penetration depth is not affected by material thickness variation. However, it is noted that material thickness variation in this operation must still be considered. To overcome the material thickness variation, a force control strategy is recommended. A force control strategy will also maintain acceptable weld surface quality.

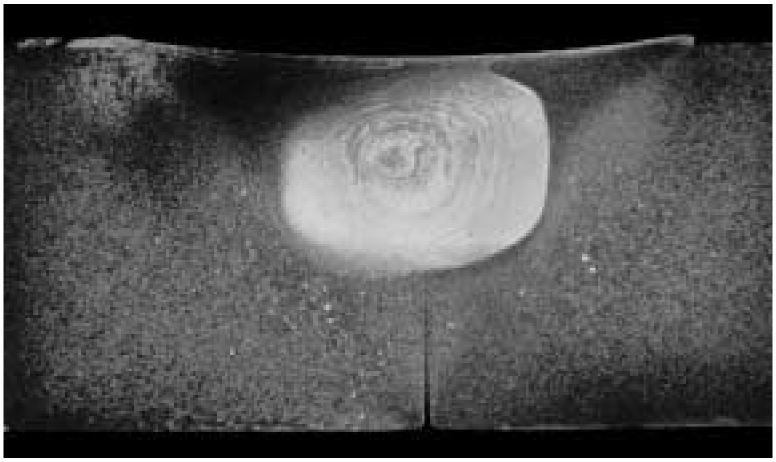

Figure 12: Partial Penetration Butt Weld Joint made in 12.7 mm 6061-T6 (7 mm Penetration)

A typical partial penetration butt weld is shown in Figure 12. The asymmetric nature of the FSW process is more readily noticeable with this joint configuration, by noting asymmetric nature of the weld nugget shape. Also, of note is that the actual penetration (depth of weld nugget) is greater than the length of the pin by about 0.5 mm. This particular weld was made in 12.7 mm material with approximately a 7 mm penetration depth. Welds in this joint configuration, with this penetration depth, can be made at travel speeds well in excess of 1 meter per minute with over 90 percent joint efficiency.

If a full penetration butt weld is required, one means of achieving this in a high volume production environment, is a variation of the partial penetration butt weld. The specific solution is to implement the double-sided butt weld. This involves making two partial penetration butt welds, with tools opposing and operated separately or simultaneously. This avoids the issue of the process sensitivity to penetration depth and the associated ease of producing "kissing bonds." An example of this type of weld is shown in Figure 13.

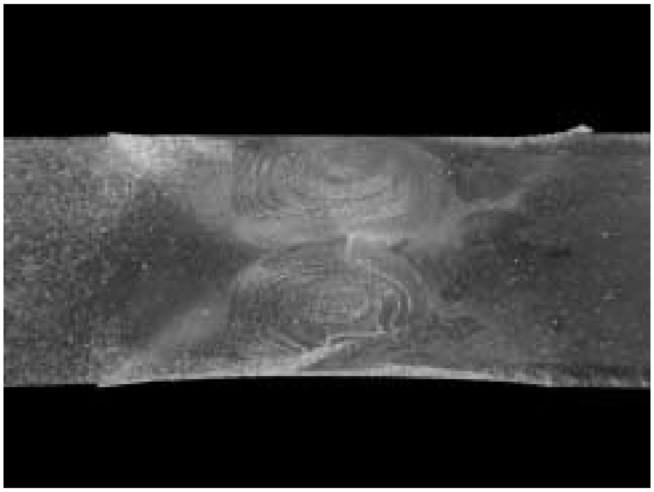

Figure 13: Double Sided Butt Weld Joint made in 12.7 mm 6061-T6

Although early in the developmental stages, this process has been shown to be capable of achieving consistent joint efficiencies of approximately 90% in 6061-T6. Early work has also shown that significant increases in travel speed are also possible, likely because of the dual heat input characteristic of this process.

Dissimilar Thickness Butt Weld

In the automotive industry, the likely application for the dissimilar thickness butt weld is the tailor welded blank. For this application, early research attempted to produce dissimilar thickness butt joints from the non-stepped side (shown in left side of Figure 14). This particular approach left a stress riser on the under side of the weld. This stress riser led to mechanical properties (tensile strength) that were less than would be expected for a similar thickness joint made in the smaller thickness material. This occurred, even with 100 percent penetration. This indicated that the notch was detrimental to the joint quality.

Figure 14: Similar Thickness Side TWB and Dissimilar Thickness Side TWB

As a result of these findings, research progressed towards making dissimilar thickness joints from the stepped side. As previously mentioned, this new approach required the tool to be tipped at an angle to the side while traveling. Similar to terminology used in fusion welding, this angle is referred to as the work angle. Also, to prevent the front side of the tool from digging into the material, the tool must also be tipped backward, as is typically necessary even on a similar thickness joint. This second angle is referred to as the travel angle. Both angles are described back in Figure 8.

The parameter development process for this joint configuration is significantly more involved. For any particular combination of thickness, the travel and work angles are unknown. This poses a challenge for tool design, as the required pin length is a function of the optimal work and travel angles. Thus, the tool design for this application becomes an iterative process. Other challenges include avoiding excessive flash and thinning on the thin material side. Both of these maladies are very easy to produce, especially if the tool is off-seam. Until a library of joint configurations and their associated work, travel, and tool designs is developed, parameter development for this configuration will be cumbersome. Also, the sensitivity to seam position would suggest that seam tracking capability will be required for this application, unless there is tight control of material width or until tool designs are developed that allow the process to be less sensitive to this variation.

With this joint configuration, joint efficiencies typical of the similar thickness joint should be observed. That is, a 5xxx O temper alloy should fail in the base material and a 6xxx series heat-treated alloys should fail in the heat affected zone. Since the heat affected zone is in the area where the material is thinned slightly, failure location is highly preferential to this area for 6xxx series alloys. Figure 14 shows a cross section of a typical weld. The weld made in Figure 14 is a 1 mm to 2 mm 6111-T4 alloy weld made at a travel speed of 1.8 meters per minute on a standard industrial robot.

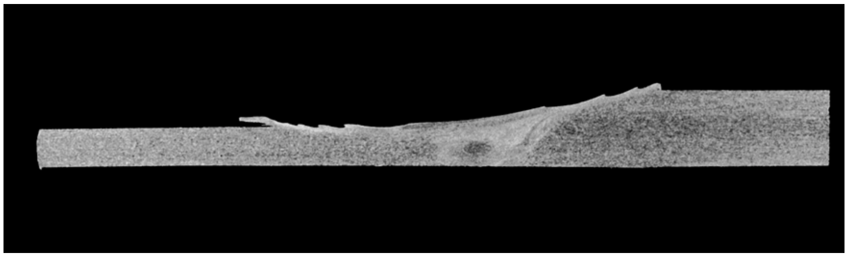

Figure 14: 1 mm to 2 mm 6111-T4 Dissimilar Thickness Butt Weld

Conclusions

FSW is an emergent technology that can be used to overcome significant limitations of other joining processes. Its inherent mechanical property advantages and operating cost advantages make it ideal for automotive application. Initially, travel speeds were poor as compared to gas metal arc welding, but travel speed improvements have been realized allowing FSW to meet or exceed GMAW travel speeds.

By proper application of the technology, the automotive industry can take advantage of the inherent advantages of the process and make its implementation a success. However, consideration for the process limitations and challenges must be made. The first consideration is to make sure the proper joint design is used. The lap penetration and partial penetration butt weld configurations are most likely to be successful.

The second major consideration is for the high force requirements of FSW. This challenge must and can be overcome. The high force requirement can first be overcome by selecting equipment specialized for the FSW process. Although commercial milling machines can be used and can generate the necessary forces, their closed architecture and inability to deal with the heat generated by the process make them poor sources for production machinery. Another issue with the high force requirements is that the welded product must be able to withstand the high forces at the point of welding resulting in the use of a backup or the optimization of the part geometry. In most cases, automotive products are designed for gas metal arc welding, resistance welding, riveting, etc., but they will be unable to withstand the force generated by FSW. Just as automotive structures are now designed for today’s production joining processes, they can just as well be designed for FSW.

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