F. Thermal-Drilling Application Development

Principal Investigators: Peter J. Blau
Oak Ridge National Laboratory (ORNL)
P.O. Box 2008, Oak Ridge, TN 37831-6063
(865) 574-5377; fax: (865) 574-6918; e-mail:blaupj@ornl.gov

Dean M. Paxton
Pacific Northwest National Laboratory (PNNL)
P.O. Box 999/K2-03,Richland, WA 99352
(509)375-2620; fax: (509)375-2186; e-mail:dean.paxton@pnl.gov

Technology Development Area Manager: Joseph A. Carpenter
(202)586-1022; fax: (202)587-1600; e-mail: joseph.carpenter@ee.doe.gov

Expert Technical Monitor: Philip S. Sklad
(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

Participants:
This project is being conducted as a partnership with USAMP-AMD[1] that includes the following automotive company representatives:
Bill Charron, Ford Motor Company
Larry Krawczak, Daimler-Chrysler Corporation
Ron Strong, General Motors Corporation

Contractor: Oak Ridge National Laboratory
Contract No.: DE-AC05-00OR22725

Objectives

- Determine the feasibility of using thermal drilling (ThD) to form fastener holes in high-strength steels and lightweight alloys in the form of castings, hydroformed parts, and sheet stock.
- Determine suitable ThD parameters for selected alloys if they prove to be amenable to the process.
- Thermally drill and tap fastener holes, measure their critical dimensions, and conduct clamp-load tests to compare ThD samples to those with traditionally-produced fastener holes.
- Develop a better understanding of the way in which the initial microstructure of the workpiece affects ThD hole quality, and in turn, the way in which ThD can affect microstructure.

Approach

- Alloys for ThD tests will be selected and provided by USAMP project team members. Thermal-drilling bits will be purchased or provided as in-kind contributions by tooling suppliers.
- ORNL will conduct ThD and tapping experiments on the selected alloys, noting which perform best. Hole dimensions and microstructures will be studied and documented.
- Where possible, methods will be developed to correct any observed hole defects. Needs for future process development will be documented.
- Maximum fastener clamp loads will be measured at PNNL and related to ThD parameters.

- The USAMP team will assess the feasibility of introducing ThD more widely in automotive component manufacturing and provide recommendations for further development.

Accomplishments

- Four high-strength steels and six non-ferrous alloys (Al and Mg-based) were obtained. Fixtures were fabricated to enable drilling of thin stock without excessive deflection or loss of frictional heat.
- Thermal-drilling conditions were found that avoid 'flower-petal' defects in Al alloys.
- Measurements were made to assess the extent to which the original stock thickness was increased by ThD.
- An improvement was made to a previous analytical model for thermal drilling and submitted for publication.
- A compilation of suitable ThD parameters for the selected alloys has begun. Alloys that worked well and those that require more process development are indicated.
- Metallographic cross-sections were prepared to study thermal-drilling-induced deformation and to investigate the differences between thread-cutting and thread-forming taps in Al.
- Clamp-load tests were begun on steels that had the best ThD response.

Future Directions

- Work will continue to complete the matrix of acceptable ThD parameters.
- Additional hole measurements and clamp-load tests are planned for hydro-formed steels.
- The drilling performance of tri-lobed thermal drills will be compared to those for four-lobed drills.
- ThD tests on M6 fasteners will be extended to include a limited number of M8 and M10 holes as well.
- Participants will identify ThD areas for future development, commercialization, and process optimization.

Introduction

Thermal drilling (ThD) is also known as "friction drilling." It is a member of a family of joining methods and surface conditioning processes that utilizes the frictional heat generated between a rotating tool and a metal part. Related processes include friction-stir welding and friction-stir processing. In ThD, a conically-tipped tool (usually metal-bonded tungsten carbide) spins against the surface of the part to be drilled, generating heat and softening the surface. It penetrates and then perforates the workpiece, as shown in Figure 1. Softened material is extruded to form a bush on the exit side of the workpiece. A small boss may also be formed on the entrance side, under the wide portion of the tool. Another version of the tool, having a cutter to remove the boss, is commercially available.

Advantages of ThD include the following:

- Unlike traditional drilling, ThD creates no chips.
- ThD does not require drilling fluid that must be handled and disposed of.
- By forming an extruded bush, ThD thickens the effective tappable thickness of thin workpieces, like sheet stock and thin-walled castings, so that weld nuts (with their added weight and assembly operations) may not be needed.
- ThD may enable designs that would be impossible due to the need to install nuts or get at the exit side of the hole.
- ThD could simplify manufacture of chassis components from lightweight materials.
- In cast materials, the ThD extrusion may eliminate the added mass of bolt bosses and thick flanges.

ThD is currently used in the manufacture of tubular hospital furniture and certain niche applications, but has not been adopted in the automotive industry where it has significant potential to enable more extensive use of lightweight, high-strength alloys.

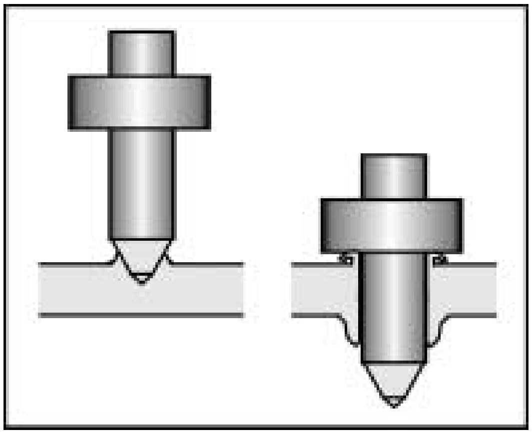

Figure 1. Schematic representation of thermal drilling. The spinning tool penetrates the workpiece to form a boss (inlet side) and bush (exit side).

The goal of this project is to demonstrate the feasibility of using ThD on ferrous and non-ferrous alloys of interest to the automotive industry. The alloys selected by the USAMP project team and provided for testing are listed in Table 1. They comprise a range of materials and product forms, and some materials were provided in more than one thickness.

Technical Approach

The technical approach draws on the strengths of USAMP team members and national laboratories. :

- Obtain alloys and determine fixturing requirements for workpiece materials.
- Obtain thermal-drilling bits from Formdrill™ and Flowdrill™.
- Determine criteria for ThD hole quality.
- Conduct and document systematic experiments on each alloy to determine suitable ThD conditions and their effects on hole quality.
- Determine which alloys can be effectively thermal drilled and which are problematic.
- Prepare ThD and tapped specimens of drillable alloys for clamp-load testing.
- Conduct clamp-load tests and compare results to traditionally-drilled holes and weld nuts.
- Assess metallurgical effects of ThD, considering both the initial condition of the stock material and the post-drilled and tapped conditions.

Table 1. Materials provided for thermal-drilling studies.

Alloy	Form
Al A380	Die casting
Al A319-T5	Die casting
Mg AZ91	Die casting
Mg AM60	Die casting
Mg AE44	Die casting
Mg AM50	Die casting
DP 600 HSS	Sheet
DP 780 HSS	Sheet
HSLA50 HSS	Sheet
TRIP 800 HSS	Sheet

The USAMP project team provides advice and critical evaluations of progress. Specifically, ORNL prepares ThD test specimens and conducts related metallurgical studies. For example, Figure 2 shows a polished cross-section of a Mg alloy in the as-drilled condition and before tapping.

PNNL conducts fastener clamp-load tests and analyses using their LabMaster Fastener Evaluation Test Cell. That unit can measure the clamp load from the installation of a fastener into a thermally-drilled hole. PNNL also determines the mode of clamp-load failure, such as thread stripping or fastener breakage.

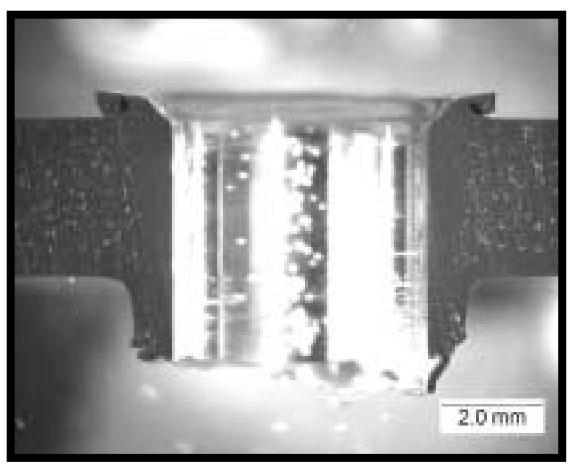

Figure 2. Polished cross-section of a thermally-drilled Mg alloy casting. The as-drilled hole interior has a bright, smooth surface finish. (The small white dots in the image are bubbles in the mounting medium and can be ignored).

Thermal-Drilling Results

In addition to the different alloys to be evaluated, the process variables used in these experiments included the following: (a) hole diameter (drill-bit diameter), (b) drill length, (c) spindle speed, (d) in-feed rate, (e) stock thickness, (f) use of drilling paste, (g) use of pre-heating or pilot holes, (h) use of several types of bits, and (i) use of thread-cutting or thread-forming taps.

A preliminary assessment was made of the ease of drilling the various materials provided. The assessment was based largely on visual observations of the quality of the bushes created using bits for M6-sized holes. Table 2 summarizes these assessments. The codes used in Table 2 to describe thermal drillability were:

- **Poor** (***P***) – not suitable (distorted or torn bushes)
- **Marginal** (***M***) – might work but requires additional studies and process enhancements
- **Special Procedures** (***SP***) – satisfactory results are obtained when using special procedures like pilot-hole drilling or pre-heating
- **Good** (***G***) – expected to work acceptably well, especially by optimizing standard process parameters like spindle speed and in-feed rate.

Most steels that were evaluated worked well for ThD, but not all. The *P* rating given the TRIP 800 was based on the formation of flower-petal-like features at the exit sides of the holes, rather than the smooth conically-shaped bushes needed for subsequent thread-forming operations.

For the steels, spindle speeds for M6-sized fastener holes ranged from about 2000 – 4000 rpm, but for the non-ferrous alloys, speeds could be as high as 10,000 rpm.

Table 2. Preliminary Assessment of Thermal-Drilling Response of Selected Alloys.

Alloy	**Form and Stock Thickness (mm)** (Note 1)	**'Thermal Drillability' Rating**
Al A380	DC (4.1)	*S P*
Al A319-T5	DC (4.1)	*S P*
Mg AZ91	DC (1.5, 3.0, 6.0)	*M*
Mg AM60	DC (3.0)	*M*
Mg AE44	DC (3.0)	*M*
Mg AM50	DC (3.0)	*M*
DP 600 steel	Sh (1.2 – 2.2)	*G*
DP 780 steel	Sh (1.15 – 2.0)	*G*
HSLA50 steel	Sh (1.14)	*G*
TRIP 800 steel	Sh (1.0)	*P*

Note 1) DC = die-cast, Sh = rolled sheet or plate

The thermal-drilling "extension factor" (EF) was used to express the additional length benefit of the tapped hole that results from the formation of an extruded bush by ThD. It can be defined as follows:

$$EF = (B + t) / t$$

where B = the length of the extruded bush on the exit side of the workpiece (in the final as-drilled and tapped condition) and t = the starting stock thickness. *EF* can also be expressed as a percentage.

Based on preliminary studies of steel and Al specimens, the EF values are given in Table 3. In general, thinner stock produces higher EF values. Values have yet to be determined for Mg alloys.

Table 3. Extension Factors for Aluminum Alloys and Steels for Thermal-Drilled and Tapped M6 Fastener Holes.

Alloy	**Form and Stock Thickness (mm)** (Note 1)	**Extension Factor**
Al A380	DC (4.1)	1.32
Al A319-T5	DC (4.1)	1.31
DP 600 steel	Sh (1.2)	2.70
DP 780 steel	Sh (1.15)	3.07
HSLA50 steel	Sh (1.14)	2.90

Note 1) DC = die-cast, Sh = rolled sheet or plate

By the conclusion of FY 2006, most of the steels on hand had been tested to provide a preliminary evaluation of their drilling characteristics. Also, ThD and tapped samples were sent to PNNL on a regular basis. Since the Mg alloys presented certain challenges, these will be further investigated in the early months of FY 2007 and suitable specimens will also be sent to PNNL. Initial clamp-load tests on the steel were promising, as the following section reveals.

Fastener Testing at PNNL

Torque-tension testing was performed using the LabMaster Fastener Evaluation Test Cell at PNNL. The Atlas-Copco nut-runner was programmed to drive the fasteners to failure and the Labmaster software recorded clamp load and input torque versus time and angular rotations of the fastener for each test. The failure mode was noted at the end of the test (break the fastener or strip the threads). A total of three tests at each combination of material and hole type has been completed and reported for traditional machine-screw fasteners with a Magni 565 coating.

Figure 3 shows the maximum clamp load and input torque at failure for both conventionally-drilled and thermally-drilled holes (both followed by tapping) in a range of alloys and plate thickness. Torque-tension testing of 1.2-mm-thick plates with conventionally-drilled and tapped holes resulted in stripped threads at ~9 Nm with a minimal amount of clamp load generated at ~6 kN. By thermally drilling the same thickness plates to increase the threadable thickness, the torque at thread stripping increased to ~17 Nm with corresponding clamp load of ~ 15 kN.

During similar testing of 2.2-mm-thick DP600 plate with conventionally-drilled and tapped holes, the holes stripped at ~16 Nm and generated ~ 12 kN of clamp load. However, after the thermal drilling and tapping of the 2.2-mm-thick DP600 plate, the fastener broke after ~17 kN of applied torque and generated ~17 kN of clamp load.

Future Work

Plans for the future include: (a) completing ThD and tapping of the ten selected alloys, (b) completing clamp-load testing, (c) determining what special processing might be required for the Mg alloys to improve their ThD response, (d) completing a compilation of suitable ThD conditions for all test materials, (e) evaluating results for four-lobed versus three-lobed ThD bits, and (f) preparing recommendations for further development of thermal drilling as a cost-savings and environmentally- friendly technology for manufacturing lightweight automotive parts.

Conclusions

Considerable progress has been made in several key areas due in part to enthusiastic collaboration among team members and by the ability to draw upon prior work at ORNL and the University of Michigan. The following conclusions were reached:

1. High-strength steels, such as DP 600, DP780, and HSLA50, seemed well-suited for thermal drilling, but TRIP800 was not.
2. The formation of extended bushes by thermal drilling can increase the tappable hole length in steel sheet products by as much as 300%.
3. Thermal-drilling conditions must be developed for the specific material being drilled and cannot be generalized for all metals and alloys in a particular class (e.g., steels).
4. Clamp-load data for thermally-drilled and tapped steels were encouraging and suggest the potential for using this method in assembling certain steel automotive components.
5. Additional research on the processing method is needed to improve the thermal-drilling results for die-cast Mg alloys, although results for cast Al are encouraging.

Publications

None this reporting period.

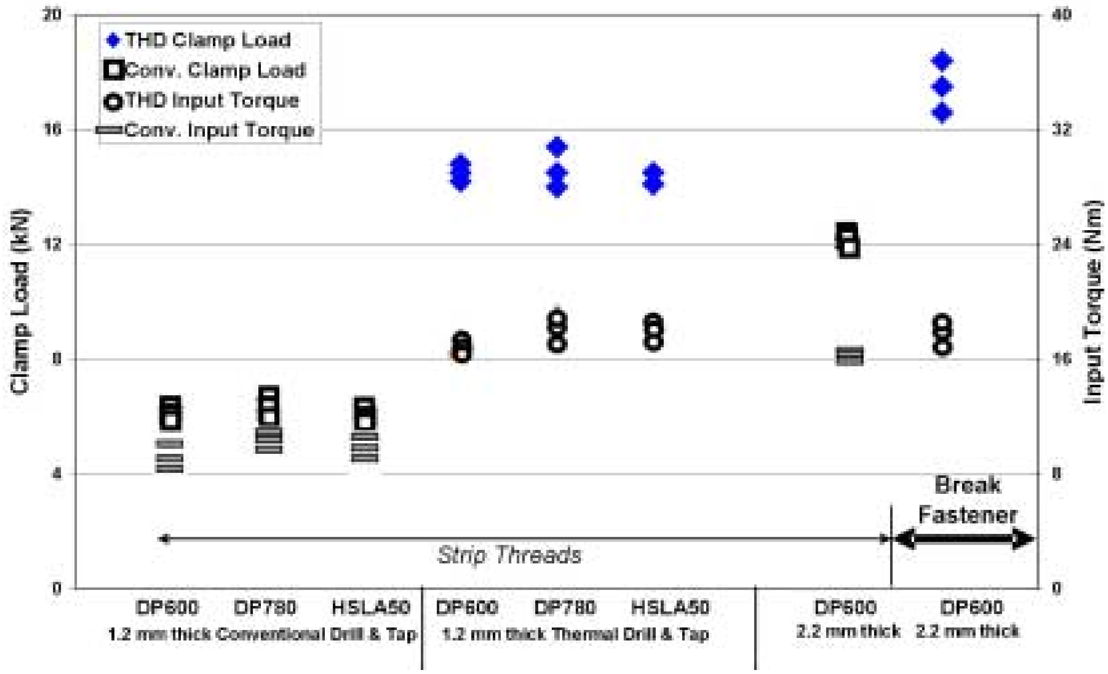

Figure 3. Torque-tension test results comparing conventional and thermally-drilled holes in a range of alloys and plate thickness.

---

[1] Denotes the Automotive Metals Division (AMD) of the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the “Big Three” traditionally USA-based automakers to conduct joint pre-competitive research and development.