Ultrasonic-Assisted Drilling of 4340 Alloy Steel

Amin Moghaddas, Graduate Fellow
Nick Wiley, Project Engineer
Matt Short, Senior Technical Advisor
Karl Graff, Principal Engineer
EWI

Introduction

Due to its toughness, fatigue resistance, and ability to retain high strength at high temperature, 4340 is an alloy steel that is widely used in the automobile and aerospace industries. Because of these properties, drilling 4340 alloy steel, especially at high material removal rates, has challenges that include heavy thrust force and torque which directly affect tool life, surface roughness, and dimensional accuracy of drilled holes. Therefore, to improve productivity of the drilling process using faster feed rates, the noted challenges should be addressed and solved.

EWI's broad capabilities in power ultrasonics have enabled it to develop an industrially hardened, ultrasonic-assisted drilling (UAD) system to address these varied challenges. This system applies high-frequency (20 kHz) vibrations at amplitudes of 2-20 µm to the drill tip in the feed direction. This system, which is fully compatible with CNC systems, is able to work with a drill at a shank diameter of up to 20 mm for a variety of materials from aluminum to Inconel and composites. The results for 4340 alloy steel are reported in this study.

Design of the UAD module

A CAT-40 UAD module developed at EWI (Figure 1) is comprised of an ultrasonic transducer, rated at 4.5-kW power, housed within a cylindrical case, the tapered front mass extending to the right from the case, the drill attached to the steel front mass by a shrink fit connection, and a CAT-40 tool holder on the left end. The drill is 16 mm and has a stickout of 11.43 cm (4.5 in.). The length of the system, from the gauge line to the drill tip, is 28.25 cm (11.12 in.). The unit is an all-steel construction to ensure production floor robustness.

The cylindrical case is acoustically designed to eliminate transmission of ultrasonic vibrations into the tool holder or other parts of a machining center. In addition to the CAT tool holder, the module may be used with hollow taper shank (HSK) tool holders. Finally, while a shrink fit collet is shown, a compression collet design is available and a hydraulic collet is under development.

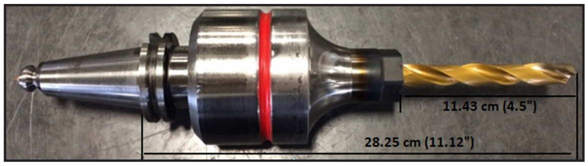

Figure 1: EWI Ultrasonic-assisted drilling (UAD) module.

The UAD module was the result of a finite element analysis (FEA) based modeling process accompanied by modifications arising made during the final fabrication and testing.

Drilling tests

Drilling tests were performed using the 4.5-kW drilling module with a through-spindle electrical connector. The module was housed in a Sharp SV-2414S CAT-40 vertical machining center and was powered by a Dukane 20-kHz, 4.5-kW power generator. After tuning and characterizing the module, drilling trials were performed in the Sharp vertical machining center using a Kistler dynamometer (Model No.: 9272) to measure thrust force (Fz) and torque (Mz). The drilled material was in the form of several 25.4-mm thick, 44.2-mm diameter pucks of 4340 alloy steel. A Blasocut 2000 series, water-based coolant was used in the flood mode to cool the drill and the workpiece. The drilled samples were tested using a Zeiss Surfcom 2000SD3 for surface roughness and a DIATEST counter-measuring unit to measure the surface finish of each hole.

A 16-mm Kennametal carbide drill bit was tuned to the module at a frequency of 19.79 kHz and amplitude at the drill tip of up to 11 µm.

To evaluate the effect of ultrasonic vibrations on drilling 4340 alloy steel, baseline settings (i.e., no ultrasonics) were first determined and thrust force, torque, and surface roughness measured. Two ultrasonic test scenarios were then conducted:

Scenario 1–Vibrations at a 100% amplitude setting of power supply were imposed on the baseline parameters;

Scenario 2–At a 100% amplitude setting, the feed rate was increased while the spindle speed was fixed.

The settings used for the baseline, Scenario 1, and Scenario 2 trials are summarized in Table 1.

Table 1: Summary of setting for three drilling trials.

	Amplitude (%)	Amplitude (µm)	Spindle speed (RPM)	Feed rate (in./min)	Chipload (in./rev)
Baseline	0%	0	1250	8.5	0.007
Scenario 1	100%	11	1250	8.5	0.007
Scenario 2	100%	11	1250	21.5	0.017

Thrust force

The values of the thrust force and torque for the baseline settings and the settings that were used for Scenario 1 are shown in Figure 2 and Figure 3.

As shown in Figure 2 and Figure 3, when longitudinal vibrations of 11-µm amplitude were applied to the baseline settings, the average thrust force and torque decreased by 42% and 24%, respectively.

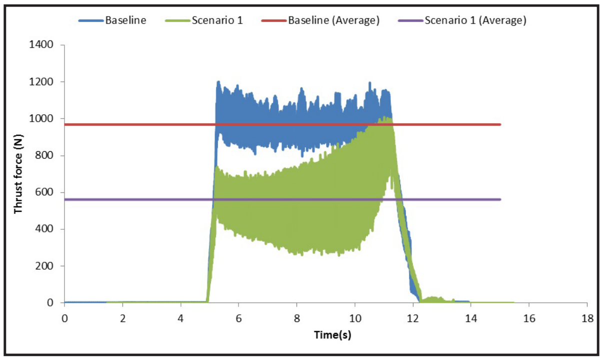

Figure 2: Thrust force data of baseline settins versus Scenario 1.

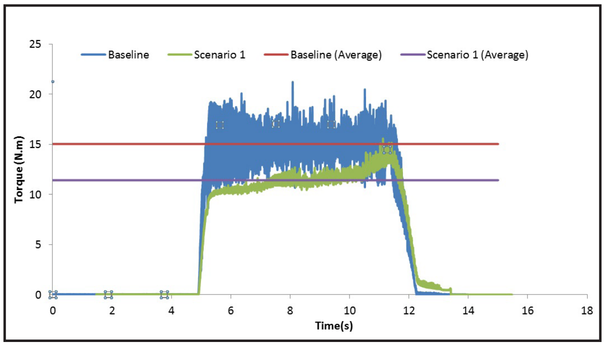

Figure 3: Torque data of baseline settings versus =Scenario 1.

Figure 4 compares thrust force data of Scenario 2 versus the thrust force data obtained in baseline settings.

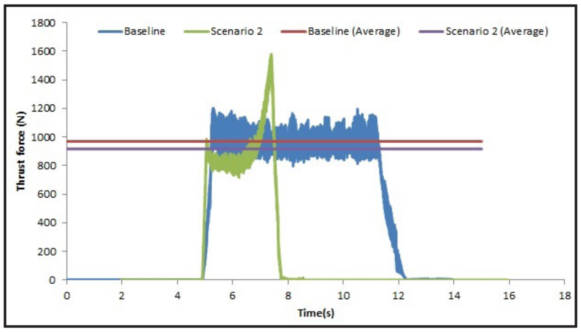

Figure 4: Thrust force data of Scenario 2 versus baseline settings.

As shown in Figure 4 for Scenario 2, even though the feed rate increased from 8.5 in./min to 21.5 in./min, the average thrust force is still less than the average thrust force at baseline settings. Therefore, by applying ultrasonic vibrations with an 11-µm amplitude, the machining feed rate can be increased up to 2.5 times, while the average thrust force is still less than the average baseline thrust force. This translates to a 250% improvement in drilling cycle time.

Surface roughness measurement

The surface roughness (Ra) of the drilled hole with baseline parameters, the drilled hole with baseline parameters using ultrasonics, and the drilled hole with advanced parameters using ultrasonics are provided in Figures 5-7.

The resulting roughness data is summarized in Table 2.

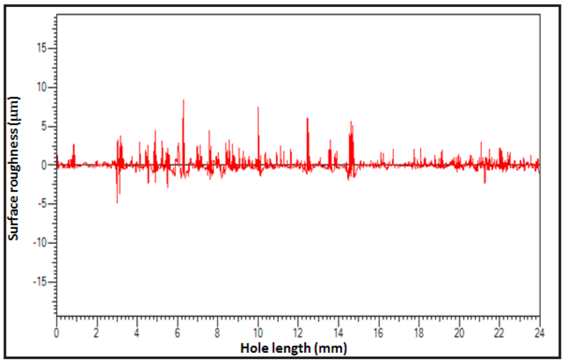

Figure 5: Surface roughness of the drilled hole with baseline settings

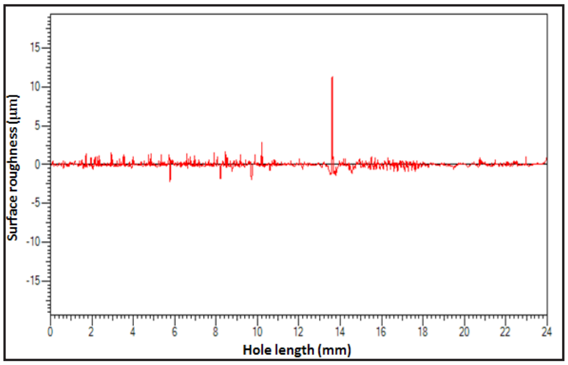

Figure 6: Surface roughness of the drilled hole at baseline settings with ultrasonic vibrations with 11-µm amplitude (Scenario 1).

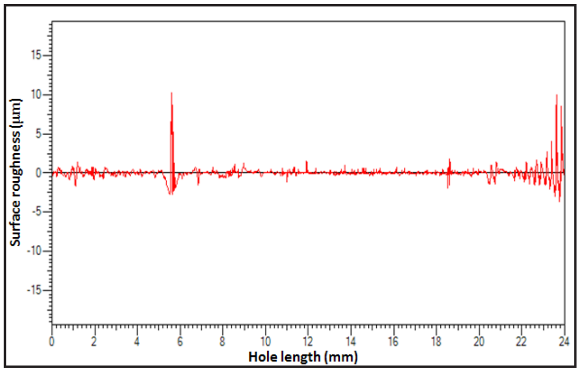

Figure 7: Surface roughness of the drilled hole at advanced parameters (higher feed rate) with ultrasonic vibrations and 11-µm amplitude (Scenario 2).

Table 2: Summary of settings for three drilling trials.

	Amplitude (%)	Spindle speed (RPM)	Feed rate (in./min)	Chipload (in./rev)	Ra (µm)
Baseline	0%	1250	8.5	0.007	0.4179
Scenario 1	100%	1250	8.5	0.007	0.2083
Scenario 2	100%	1250	21.5	0.017	0.3431

As shown in Table 2, the test performed using baseline settings with an 11-µm amplitude (Scenario 1) improved the surface finish by more than 50% compared to the results without using ultrasonics (baseline). In comparing the results of surface roughness of the holes drilled with baseline settings and the holes drilled in Scenario 2, there is an 18% improvement in surface roughness with a significant increase in productivity (increasing the feed rate from 8.5 in./min to 21.5 in./min).

Conclusion

The ultrasonic-assisted drilling of 4340 alloy steel was evaluated, using the robust, all-steel UAD system developed at EWI that is fully compatible with CNC machining systems.

The results of two test scenarios are reported and the results, including thrust force, torque, and surface roughness are compared to baseline settings. In Scenario 1, ultrasonics reduced the thrust force and torque by 42% and 24% respectively, while the surface roughness of the hole is improved by 50%. In Scenario 2, the feed rate increased by over 250% before conventional thrust force levels were reached, thus achieving a major increase in potential productivity. This increase is achieved while the surface roughness of the hole is improved by 18%.

***Amin Moghaddas**, EWI Graduate Fellow, is a PhD student at The Ohio State University. His work focuses on improving manufacturing processes by applying high-power ultrasound to enhance the performance of conventional manufacturing processes, specifically the ultrasonic-assisted drilling (UAD) process.*

***Nick Wiley**, Project Engineer, is a member of EWI's ultrasonics group. He works with a broad range of advanced manufacturing processes including ultrasonic-assisted machining, ultrasonic welding, resistance and solid state welding, and laser processes.*

***Matt Short**, Senior Technology Advisor, is renowned for his expertise in ultrasonic systems, plastics assembly, automated system design, tool and die design, and CNC/CAM programming. He is the inventor of AcousTech™ machining, a cutting-edge ultrasonic application that can improve the performance, enhance the productivity, and extend the life of conventional metalworking equipment and tools.*

***Karl Graff**, Senior Engineer, is an international authority in the field of high power ultrasonics, including transducers, applications, and systems. He led the effort to found EWI in the early 1980s, and served as the company's executive director from 1987-2000. Since 2000, he has continued his research in ultrasonics, soldering/brazing, welding, additive manufacturing, machining, and forming.*