Integrating Jominy End-Quench Test Apparatus from Senior Design Project to Mechanical Engineering Labs

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Abstract

An important element of engineering teaching is related to laboratory investigation focused on real life applications via experimental learning. Labs introduce opportunities for students to practice and participate in scenarios that could enhance their professional experience while preparing them for engineering careers. A senior design group of two mechanical engineering and one industrial management students designed, manufactured and implemented a Jominy end-quench test apparatus built to ASTM standards. The testing equipment will be further integrated into an engineering lab where students can investigate the effects of the heat treatment processes and measure the hardenability of various types of steels. In order to ensure the successful design for construction and implementation of the Jominy tester, senior design students use concurrent knowledge of fluid mechanics, materials science and heat transfer in addition to industrial management for planning, production, optimization, ergonomics and safety.

Keywords

Jominy end-quench test, hardenability, steel quenching, hardness testing, senior design

Introduction

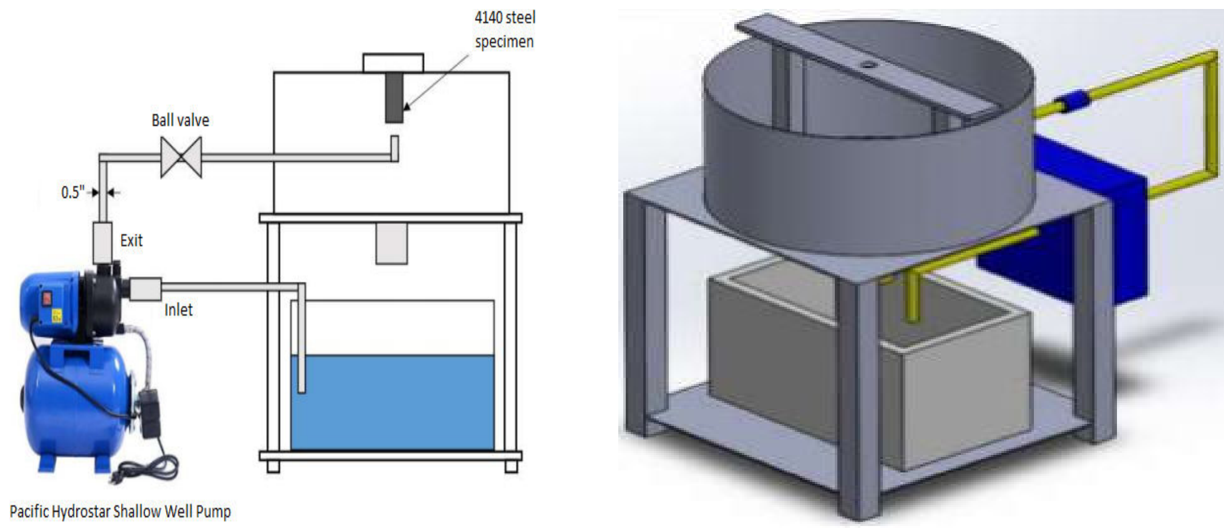
In order to have an accredited engineering program by the Accreditation Board for Engineering and Technology (ABET), engineering programs must show they meet the general criteria for accreditation which includes student outcomes. These student outcomes are divided into seven areas and are detailed in the accreditation manual [1]. Few of the student outcomes are envisioned for this project completion, including Outcome 5 and Outcome 6. Outcome 5 states that the students must show that they have the ability to function effectively on a team whose members establish goals, plan tasks, meet deadlines, provide leadership and create a collaborative and inclusive environment, which applies to the senior design group on this specific project. Outcome 6 states that the student must show that they have the ability to develop and conduct appropriate experimentations, analyze and interpret data, and use engineering judgement to draw conclusions which will apply to the qualification of the design by the team for usage in a laboratory setting. The specialized engineering laboratories related to courses that are integrated within the college of engineering curriculum exposes students to learning through experiments and simulating realistic applications. By using large equipment diversity to solve different problems resembling industrial environment, students have the possibility of tailoring their own approach to engineering related solutions. Two mechanical and one industrial engineering students were expected to design and build a Jominy quench-end equipment during their senior design project and to implement the testing procedure for creating a laboratory class. It is anticipated that

apparatus will be used to investigate the effects of heat treatments on the hardness of quenched steels and for analyzing the hardness
correlation with other mechanical properties (i.e. yield, tensile strength) and microstructures. The Jominy testing apparatus works in conjunction with already existing equipment: high temperature furnaces, hardness tester, optical microscopes and requires additional small machining operations for testing completion.
In order to solve engineering related problems, it is important for students to become familiar with standards, their content and with established procedures. The American Society for Testing Materials offers guidance and provides general standardized testing methods for analyzing specific situations. For example, the Jominy end-quench test, also known as hardenability test is standardized by the American Standards for Testing and Materials (ASTM) under the standard A225-02 [2] and is reproducing the hardening of the sample from the surface to the interior by monitoring the hardness values at different distances from the quenched end.
Testing the plain carbon and alloyed steels hardenability is an important step in selecting appropriate materials and heat treatments parameters for different applications, as well as for minimizing thermal stresses, potential distortions and fracture occurrence in components with large dimension variations [3]. The hardenability of the steel alloy is the depth of hardening the material from the surface to the interior [3] during performing the heat treatment process involving corresponding heating and quenching procedures.
The ultimate goal of the senior design team work is to design, build and implement a fully functional Jominy testing apparatus in compliance with the ASTM standard that will be used for mechanical engineering laboratory classes for testing alloyed steels, helping students getting familiar with hardness testing and in particular to investigate the hardenability of the 4140 steel. The laboratory will address the ABET requirements by offering students the "ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgement to draw conclusions".

Experimental Methods

The specific requirements for performing the Jominy end-quench testing in order to accurately define the hardenability of the steel alloys are provided by the ASTM standard A225-02. The testing specimens with standardized shapes and dimensions are undergoing normalization heat treatment to ensure the similar initial structure. Samples are heated according to standard and immediately quenched using the tester. As described by the standard, the cooling water flow must extend 2.5" above the orifice without the specimen mounted on the fixture. As the specimen is put in the place for cooling, the 0.5" distance between the orifice and bottom face of the specimen must be ensured. In order to respect the tester functionality according to standards, a valve must control the stream of water and provide the standardized flow and pressure. After the quenching process, two parallel and flat, planar surfaces at a depth of 0.015" are milled on the specimen. The Rockwell hardness C (HRC) measurements are performed along the length of the bar on two machined, flat parallel surfaces. The distance between two consecutive hardness measurements is provided by standard. It is expected that the quenched end of the specimen that is directly cooled with water will exhibit a 100% martensitic structure. The rate of cooling decreases as the distance from the quenched end increases, hence the hardness of the specimen decreases accordingly with the distance.
The Jominy end-quench tester must be constructed such that the support for testing the specimen is able to withstand temperatures in the 1700 +/- 100 °F range and have a water tank that allows

the water circulation during the quenching procedure. The metallic components should be able to resist corrosion. Filters must be installed in order to prevent scaling from circulating through the pumping system. Adequate sealing must be provided to prevent possible leaks in the pipes and in the entire apparatus. Figure 1 is showing the schematic view of the Jominy end-quench tester (a) and the solid model of the accepted design (b). The Pacific Hydrostar pump is used to pump the water from the tank ensuring an adjustable flow and pressure. During the quenching process the water is drained in the tank situated below through a drain. All the pipes used for the pumping systems are made of polyvinyl chloride (PVC) with 0.5" in diameter.



(a) (b)

Figure 1. Jominy end-quench tester: schematic view (a); solid model (b)

The materials selected for building the testing apparatus are: A36 steel plates, A36 bars, AISI 1010 steel sheet, PVC tubing. The legs of the apparatus consisted of 2" square and 0.25" thickness wall steel tubing (in house) that are cut to the same length by using the horizontal band saw and the mill. The Figure 2 illustrates the welding processes for connecting the legs to the bottom of the top plate (a), the stubs onto the bottom of the top plate (b) and final attachment of the top and bottom plates (c).

(a) (b) (c)

Figure 2. Welding procedures: legs to the bottom of the top plate (a); stubs to the bottom of the top plate (b) top and bottom plates together via legs (c)

Figure 3 highlights different stages of the manufacturing process. In order to create the circular enclosure of the tester, the AISI 1010 sheet is machined by using the sheet roller located in the machine shop (engineering building) that is represented in Figure 3 (a). A hole is created in the top plate by plasma cutting (Figure 3 (b)) and the remaining jagged edges of the top plate are finally removed (Figure 3 (c)). After creating the circular enclosure, the ends of the sheet are fastened together to retain the shape and then joined by rivets. The circular enclosure is attached to the upper A36 plate.

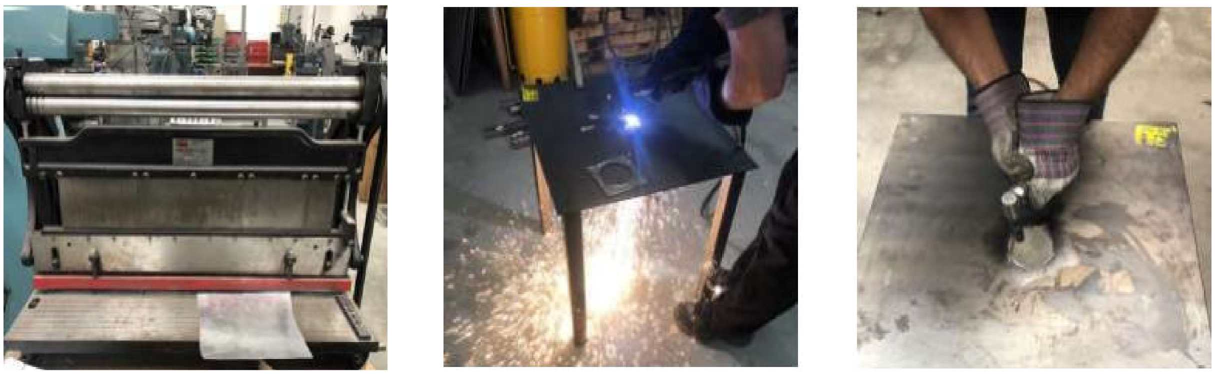


Figure 3. Stages of the manufacturing process: sheet rolling the circular enclosure (a); plasma cutting top plate (b); removing of the jagged edges of top plate (c)

The apparatus was entirely painted in order to prevent corrosion resulting from the circulating water. The apparatus manufacture was completed in the machine/ weld/ wood shop and it was placed in the materials lab in the vicinity of the high temperature heating furnace in order to ensure a fast transfer of the specimens from the furnace after heating to the Jominy tester support for quenching. The height of the support was also designed to ensure a fast transfer. Figure 4 shows the final shape of the manufactured Jominy quench-end testing apparatus (a) and the placement of the apparatus in the materials laboratory (b).

(a) (b)

Figure 4. Completed Jominy end-quench tester (a); placement of the tester adjacent to the laboratory furnace (b)

Results and Discussion

After finalizing the construction, different tests were conducted to ensure the functionality of the apparatus. These tests included testing of the pump, safety tests and anthropometric tests to ensure the tester ergonomic use [4]. The Pacific Hydrostar Shallow Well pump was tested to ensure that the pressure and the flow rate provided by the pump are constant throughout the entire process [5]. The compression tank was pressurized to a constant 23 psi air pressure by connecting the bicycle pump to the air valve located at the end of the compression tank.
The AISI 4140 testing specimen was manufactured to the specified ASTM standardized dimensions and initially heat treated for normalization. Following the normalization treatment, the sample was heated in the furnace according to the standardized conditions for temperature and time and was quenched using the Jominy end-quench apparatus. Figure 5 is showing the picture of the standardized size specimen (a) and the Jominy quenching procedure after the sample was removed fast from the furnace and placed in the Jominy test support (b).


(a)


(b)

Figure 5. Jominy end-quench specimen: manufactured standardized specimen (a); standardized quenching of the test specimen (4140 steel)

After finalizing the quenching, the specimen was cooled and was removed from the apparatus. Two parallel flat surfaces were machined on the specimen at a depth of 0.015", according to the standard. Rockwell C hardness measurements were performed on the specimen at every 1/16" for the first inch from the quench end and then hardness measurements were performed at every 18, 20, 22, 24, 28 and 32 sixteenths of an inch from the quenched end on both sides. The hardenability curves were obtained for each side showing similar results and a decrease in the hardness with the distance from the quenched end.
A typical AISI 4140 steel hardenability curve is depicted in Figure 6 and it was obtained with the designed Jominy tester. Three hardness measurements were performed at standardized specified distance on each side of the specimen with similar results. The curve showed a 32% decrease in hardness form the quenched end to a depth of 2 inches. The recorded hardness at the quench end had an average of 54 HRC +/- 2 and the average hardness at a depth of 2 inches was 39 HRC +/- 2.
The location of the Jominy testing apparatus in the furnace proximity was determined based on safety concerns and on the time constraints for a fast transfer of the specimen from the furnace to

the tester. The specimen requires starting the quenching procedure within the five seconds after removal from the high temperature furnace.

Due to the use of high temperature furnaces for performing the Jominy testing, the safety concerns are a key part of the testing. High temperature gloves, face shields, and furnace lab coats must be used to ensure that the risk of injury is minimized. Other protection methods include wearing long pants and close-toe shoes to secure the operator from possible flakes falling from the hot specimen during transportation between the furnace and the tester.

The tester must have an ergonomic design with dimensions that are ensuring an easy usage. The design of the apparatus was tailored such that most people could use the apparatus in a comfortable manner. Available anthropometric data [4] were used to determine the correct height for a comfortable use and to make possible a fast transition from the furnace to the apparatus for quenching.

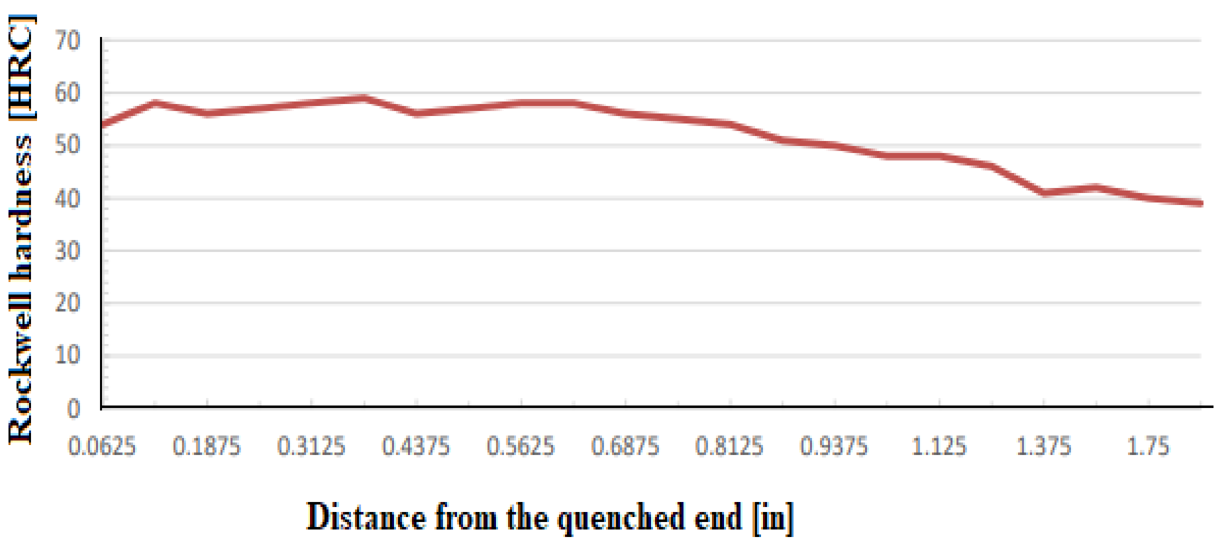


Figure 6. Typical AISI 4140 steel hardenability curve

Conclusions

The addition of the Jominy quench-end testing apparatus to the laboratory offers "hands on" opportunities to conduct different heat treatments for various types of steels and interpret the results in order to analyze the quenching processes efficiency. The designed and manufactured product can successfully conduct Jominy quench testing according to ASTM standardized conditions on different types of steels enabling the implementation of the procedure in the mechanical engineering introductory lab. The equipment was used for testing the AISI 4140 alloyed steel and results were relevant for describing the hardenability of the steel. This correlates directly with Outcome 6 of the ABET Student Outcomes for engineering programs regarding the ability to develop and conduct experimentation as the student team conducted experiments to verify the usage of the device and its ability to conform to the ASTM standard. Also to Outcome

5 concerning the students "ability to function effectively on a team whose members establish goals, plan tasks, meet deadlines, provide leadership and create a collaborative and inclusive environment" as the student team had to design, build, and test the device over a two semester course in the senior year.

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Biographies

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Dorina Marta Mihut is an Associate Professor in the Mechanical Engineering Department, Mercer University. She graduated with a Ph.D. in Materials Science at the University of Nebraska-Lincoln, a Ph.D. in Technical Physics at Babes-Bolyai University, Romania, MS in Mechanical Engineering, University of Nebraska-Lincoln, and BS in Mechanical Engineering at Technical University Cluj-Napoca, Romania. Her teaching and research interests are in the area of materials science and engineering, thin films and coatings depositions using physical vapor deposition systems and related analysis, coatings for wear and corrosion resistance improvement, environmental protection, protection against electromagnetic interference, and antibacterial coatings. Before joining Mercer University, Dorina Mihut worked as Associate Professor at The University of Texas-Pan American, TX, USA, and as Process Engineer at Ion Bond, IHI Group, USA.

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