Title: Design and Development of a Continuous Annealing Laboratory Simulator (CAL-VS1) To Study Advanced High Strength Steels (AHSS) and other Steel Systems.

Work Scope: Steel Research & Applications Grant (SRAG)

PI: C. Isaac Garcia, University of Pittsburgh

7. Proposal Summary Page

The main objective of the proposed research is to explore the feasibility of designing and developing a Continuous Annealing Laboratory Simulator (CAL-VS1) as a new research equipment facility. This work will provide a multidisciplinary opportunity for graduate and undergraduate students to work in partnership using their creativity, initiative and engineering education. Another important objective is to introduce the students to an area of current interest to the steel industry. One of the responsibilities of the university in our society is to educate and to prepare, both intellectually and personally, young people for their future career and life. Universities are innovators, the research engines of our society. Universities create new knowledge. The number of breakthroughs and innovations that are generated in universities is unlimited. However, one cannot dismiss or ignore the fact that universities operate under the same universal principles of supply and demand that control the industrial world. As industry demands students with knowledge and skills in certain specific areas, university programs must be created or expanded to meet those demands. The proposed work was conceived with the idea of bringing together graduate and undergraduate students from different academic disciplines to design and build a research system that will be used to study the evolution of microstructure-property relations in AHSS and other modern sheet steel systems.

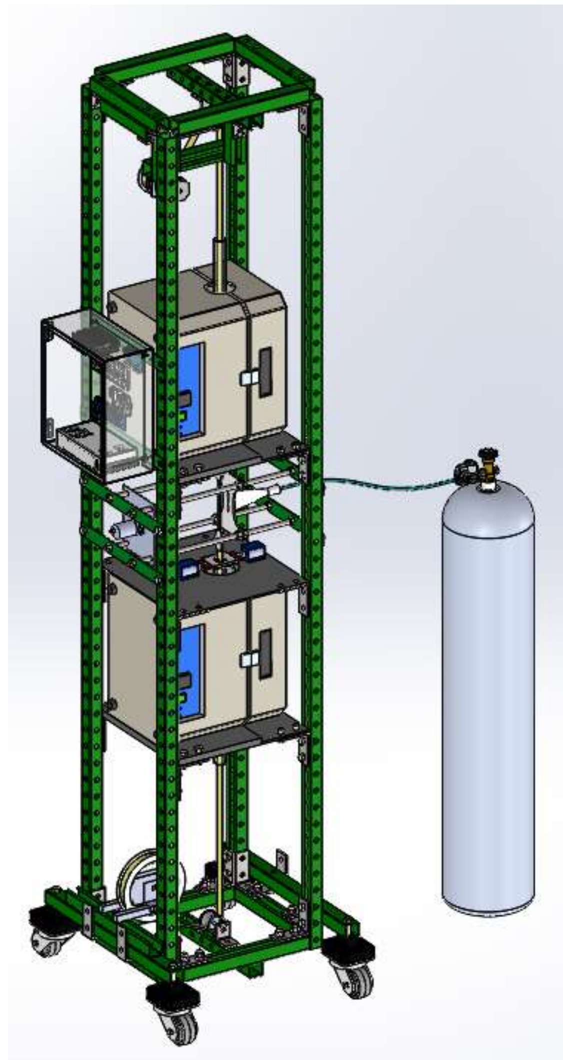
To achieve the objectives of this proposal a team of graduate and undergraduate students from the MEMS (ME & MSE) and IE departments was formed. The members of the team have interests and expertise in different technical areas that are believed to be essential for the success of the proposed project. These include but not limited to: 1) computer CAD/CAM design; 2) process controls and electronics; 3) machining and assembly; 4) additive manufacturing or 3D rapid prototyping; 5) advanced microstructural characterization and mechanical test. Based on their individual expertise and interests, project-tasks will be assigned to each team member. The logical path to carry-out the project will be conducted according with the following specific tasks or challenges: 1) setting up the CAL simulator framework and assembling each of the required devices with high accuracy; 2) developing the protocol to position the test sample smoothly using a stepper motor; 3) PID controller for the furnaces to achieve required temperature controls; 4) design and construction of the cooling system and accessories; 5) developing the control system to measure in real-time the temperature of the test sample while recording data and plotting trend curve; 6) isolating the cooling system from furnaces using solenoid-control gates; and 7) programming the central control system of the CAL-Simulator.

The performance period will be September 1st, 2015 to August 31st, 2016.

8. Detailed Project Description

The continuous development of Advanced High Strength Steels for the automotive industry requires both novel alloy steel design and unique experimental systems that will help in the fundamental understanding of the composition-processing-microstructure-property relationships. The success of this proposal strongly depends on the ability to design, develop and manufacture a laboratory CAL-Simulator VS1, described below.

CAL Simulator System Brief Introduction:



(1) Mainframe Construction:

Unistrut frame, boards and wheels assembled and fixed, supporting all the devices for the simulator.

(2) Sample Positioning & Transportation Module:

Holding fixtures connected with a stepper motor and coil spring by two spring steel strips, through guides and pulleys, transports the sample through heating and cooling modules.

(3) Heat Treatment Module:

Two furnaces are available to conduct supercritical, intercritical and subcritical annealing treatments. The sample will travel through the furnaces protected by a quartz glass tube.

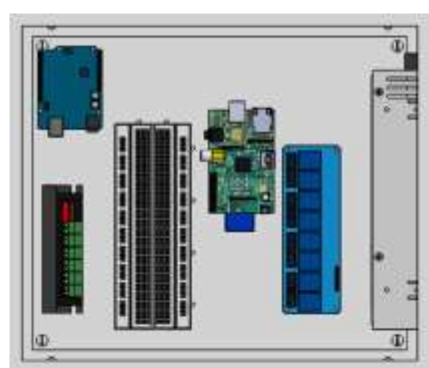
(4) Cooling System Module:

The cooling head was designed and manufactured using additive manufacturing or rapid 3-D printing. The cooling head will be linked to Helium gas lines. The flow rates will be controlled by gas flow meters to achieve the desired cooling rate up to 100 ^{O}C/sec.

(5) Electronic Gates Module:

Gates controlled by solenoids, these gates prevent the cold gas entering the heat treatment modules and keeping the sample at constant temperature during the annealing process.

(6) Temperature Detection Module:



Two infrared sensor facing the sample and d/a conversion device, to provide non-contact real time temperature monitoring during heating and cooling process.

(7) System Control Module:

Micro-controller and control units including stepper motor driver, Arduino, breadboard, Raspberry Pi and 8-channel relay board, in an electronic enclosure with a 24VDC power supply.

Task #1: Mainframe Construction

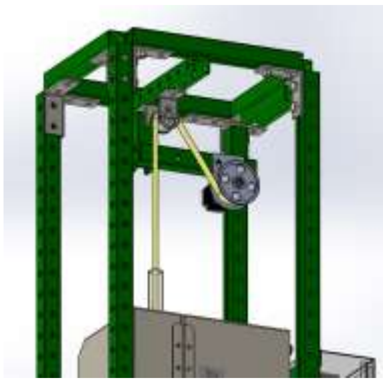
The laboratory CAL-VS1 system consists of several components, which have to be designed, machined, purchased and assembled together. A team of students has the task to design and put together the structure of the mainframe. The mainframe has the following performance requirements:

(1) Adequate load bearing capacity: the structure must be strong and stable enough to support all the auxiliary equipment safely.
(2) Sufficient stability during experimental procedures.

The students have designed the mainframe as shown in the figure above. This frame will be constructed with unistrut, girders and fasteners including screws, nuts and other necessary items. The dimensions of the mainframe are based on the size of the heat-treatment furnaces. In our concept the heating units are placed vertically. The two furnaces are perfectly aligned with respect to each other. The system has an adjustment device to make sure that the motion or path of the sample through the furnaces is centered and free to move vertically. The CAL system is equipped with wheels to allow its mobility; these can be locked up in position and the system becomes very stable and fixed.

Task #2: Sample Positioning & Transportation Module

An important task in the CAL system is to keep the sample steady while moving through the heating and cooling stages. To achieve this, it was decided to use spring stainless steel strips.



The AHSS or any sheet steel sample will be held in the specially designed fixture. This is connected to a stepper motor at the top and coil spring in the bottom by two spring steel strips. A micro-controller will control the operation of the stepper motor, so the sample will move specific distance at specific speeds. In this way the position of the sample can be exactly controlled in the heating zone of the furnaces or in the cooling zone. When the motor stops and releases the strip, the sample will be pulled back by the coil spring to the bottom, where we load or unload it. In the path of the strip we will add pulleys to keep it coaxial with the glass tubes in the furnaces. In addition, guides will be added to keep the string steel steady and prevent deviation from the pulleys.

Task #3: Heat Treatment Module

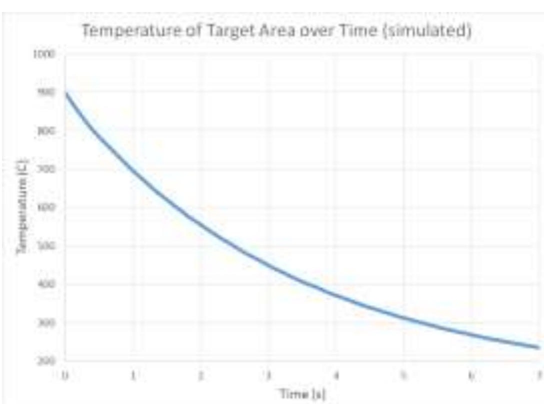
The upper and lower furnaces will be fully-computer controlled to provide the required heating cycles. The furnaces have a quartz glass tube through the hot chamber; the quartz glass tube will be filled with argon to protect the samples against oxidation if required. The micro-controller sends the required set-points one by one to the temperature controller of the heating furnace, and then it will heat up smoothly along any temperature cycle required. The temperature of the sample will be monitored by the use of an infrared sensor that will be placed at the middle of the hot zone of the furnace.

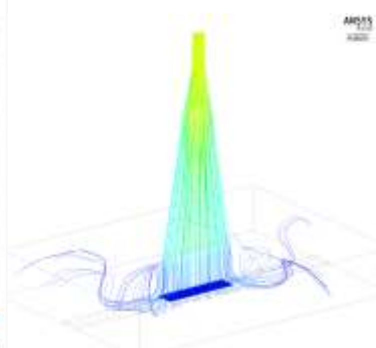
The set-up and operation control of the CAL-VS1 system will be user friendly. All the operations will be integrated to a graphical user interface (GUI) on the computer screen, as shown in the figure below. The mouse and/or the keyboard will be enough for operating the system easily and efficiently. The expected temperature curve and the actual one are both plotted, upon which we can monitor the heating process and analyze current performance.

Task #4: Cooling System Module

The cooling component of the CAL system sits between the two furnaces and is capable of cooling a metal sample very quickly using helium gas. It includes a custom-designed, 3D-printed nozzle that distributes helium coolant over a two-inch region of the sample, as well as the necessary equipment to deliver coolant to the sample at any rate from 0 to 120 standard cubic feet per minute. Our simulations show that we will be able to cool a 900°C steel sample to 300°C in just over 5 seconds. In the second figure, the blue region is the area actually cooled by the cooling system.

The cooling system will consist of four major components. First, a helium tank fitted with a two-stage regulator supplies coolant to the system at a constant pressure. Then, a gate valve precisely regulates the flow of gas through the system. This valve allows us to select any desired rate of cooling. The third component is a high-capacity flow meter, which keeps track of the coolant flow and ensures that each sample is being cooled at the appropriate rate. The flow rate in each experiment will be recorded in the database for further analysis. Finally, we have designed a custom 3D printed nozzle to evenly distribute the gas over the chosen area of the sample.



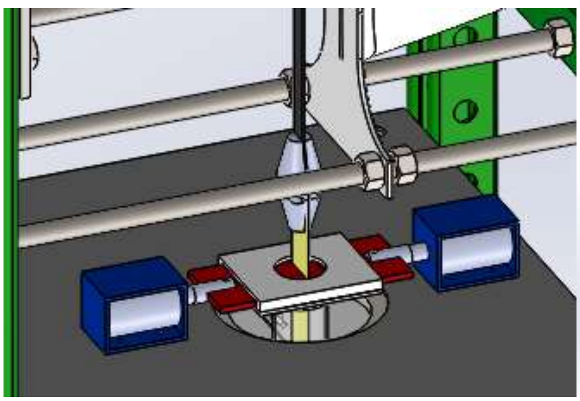


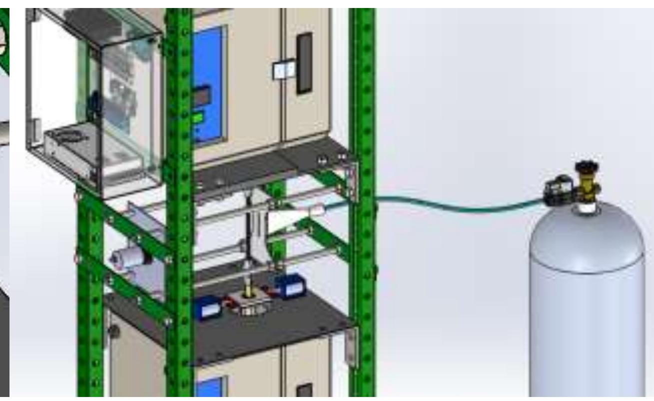
The most important part of the cooling system is the nozzle that delivers gas to the sample. We used ANSYS CFX to model over fifty different nozzle designs before selecting one that combines a high flow rate with very even cooling across the central part of the sample. The final design includes a narrow body that flattens out the flow and a tapered outlet that evenly distributes the gas. This allows for very fast cooling over the middle of a sample; our simulations predict that at maximum cooling rate, the system can bring the center two inches of a sample from 900°C to 300°C in less than 5 seconds. This cooling system will be capable of simulating a wide variety of cooling conditions typical of industrial-scale CAL plants.

Task #5: Electronic Gates Module

In our design the furnaces and the cooling module will be protected by electronic gates. These gates isolate the heating and cooling systems from each other. There are two sets of gates beneath the upper furnace and above the lower one respectively. The electronic gates are connected to controllers (solenoids) linked to Arduino, so they share data with the stepper motor.

The operation of the electronic gates can described as follows; when the sample is in the heating process, the gates are closed tightly to keep-in all heat in the furnace. When the sample moves toward the cooling zone, Arduino will calculate the distance and send a signal to the solenoids, which open the upper gates to allow the sample through. Then the sample stops at the cooling nozzle and the gates are closed, so the air flow in the cooling process will have no effect on the furnaces. When the cooling process finishes and the sample moves to the next furnace, the lower gates are instructed to open. They close after the sample passes to isolate the furnace from the cooling zone. All the codes are added in the main program. The gates will coordinate with the stepper motor to avoid any potential collision.





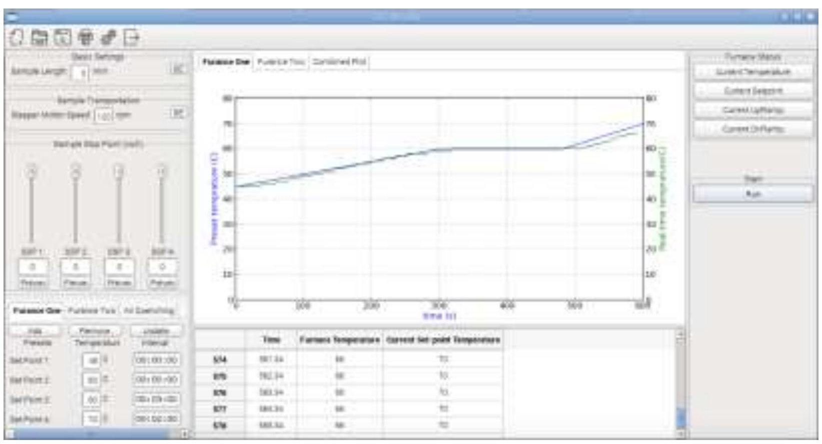
Task #6: Temperature Detection Module

This is one of the most important modules of the system. The temperature changes during the heating and cooling cycles will be monitored by two infrared sensors. One located in the main furnace and the other in the middle of the cooling zone, facing the center sample. The sensors will continuously monitor the temperature of the sample during heating and cooling. Any changes or deviations from the required heating or cooling rates will be easily adjusted. The accuracy of the temperature measurements will be 0.5°C. In order to acquire 0.5°C accuracy of the heating or cooling cycles we need to have a sampling rate over 200Hz. Based on these requirements an Infrared (IR) sensor is selected to act as the temperature detector. Due to the fact that no digital IR temperature sensor on the market at a cost-effective value can provide sampling rate higher than 10 Hz, an analog IR sensor is adopted. The analog voltage signal acquired by the IR sensor is converted to digital signal by a 10bit ADC MCP3008, and then transmitted to Micro-controller in SPI protocol. In the Micro-controller, the digital voltage signal will be processed and converted to temperature.

Task #7: System Control Module

The control system module is essentially the brain of all the devices while the other components are physical extensions that allow the work to be done. Raspberry Pi is chosen to be the micro-controller which is responsible for a variety of computational tasks integral to the functionality and utility of the superstructure.

(1) Graphical User Interface: Originally, an Arduino was going to be used for the processing and computation power of the brain. However, tests illustrate that the Arduino is not strong enough to play the role of graphical user interface (GUI). The breadboard, which essentially allows easy modifying and usage, removes the need to solder circuits onto a board because it simply needs placement into the specific slots that are allotted for each specific function. The graphical user interface ensures that the user does not have to type in computer commands into a command line but rather control the system through a convenient interface. Besides having physical extensions, the Raspberry Pi, would also have data monitoring extensions that would have the duty of reading the data. The relationship between the Raspberry Pi and its data collecting extensions is “master” and “slave.” The Python programming language is used in order to codify the instructions that the Raspberry Pi and its associated extensions would perform. While the Python language is the underlying basis for the instruction development, the furnace system has its own command structure that will allow the modules to be communicated with.



(2) Communication & Command: The two primary functions of the control system are reading and writing data. A common code with slight deviations is sent by the Raspberry Pi in order to invoke the extension to gather the temperature data. A different code structure is sent by the Raspberry Pi so that the extension would write the gathered data into the Raspberry Pi. The written data is compiled within charts for analysis. The written data is also plotted onto a graph in order that a physical representation of the temperature change within the metal can be viewed and trends could be easily observed before the careful quantification and regression that would allow a much more detailed analysis of trends. Real time graphing is done on the Raspberry Pi independent of the collection devices but using the data that is collected and also put into charts. Each time the Raspberry Pi issued a read or write command, it would only produce one instance of action at the given moment of time. Thus, a loop structure would have to be created to continually issue commands within a specified time interval. The loop structure would also be responsible for slightly modifying the issued command each time in order that it would correspond to a different value of data being collected. The frequency of the data collection is of big importance because a greater amount of data items per second would

allow a more accurate representation and better analysis. The visual representation of the better analysis available is that the graph that is generated will be much smoother with more points.

(3) Recording in Database: We will use database to record real-time data including time, interval and temperature. In this way we can relax the memory of the computer chip to increase calculation speed. Firstly, with the starting-up of the system, the database is also initialized and a unique table for a certain sample is created. The rows are sequence number, current time; interval from the starting point, temperature detected on the sample, and any other needed data relating to the sample. Secondly, during the heating, cooling and annealing process, every point will be recorded in the database. The frequency is flexible so we may read the temperature several times a minute during the long-period heating process, or check the status tens of times a second when the temperature declines rapidly by cooling. Thirdly, the record in database can be read at any time for plotting the trend diagram. And after the whole heat treatment, we can export the data to text file to study the details. We can set high degree of accuracy for time to reduce possible error.

9. Project Schedule

Week 1-2 (Concept Design):

Discuss and Design the concept of the sample transportation system, this task includes the arrangement and alignment of the furnaces, pulleys, recoiler, selection of the actuator and controller, and how to install the infrared sensors to measure the temperature of the sample. Also assign specific tasks for each team member.

Week 3-7 (3-D Modeling & Computer Simulation):

Design, create 3-D modeling of components of the main frame of the system and the sample transportation module, and purchase all the necessary components; including the unistrut body (as the main frame to place the heat treatment module), stepper motor, motor mount and motor pulley, top and bottom guidance pulleys, sample clamps, solenoid gates, and recoiler. In the end, make an assembly including all above parts. All this modeling works will be accomplished in Solidworks x64. Another student will work on the cooling nuzzle, anaylze possible air flow, complete simulation with ANSYS CFX and optimize the design.

Week 8-17 (Components Fabrication):

Fabricate or purchase basic components of the transportation module, assemble them and do tests to improve the accuracy and stability of the system. Most components (e.g. all the mounts for pulleys and the stepper motor) will be manufactured at the workshop of the university.

At the same time, start building communication network in the system. (1) Establish an interface between Raspberry Pi and Arduino via I2C communication. Code for Raspberry Pi and Arduino will be developed in Python and in Arduino IDE, respectively. (2) Build the connection between Raspberry Pi and the furnaces. Devices are connected by RS485 serial cable, using PC_LINK_COMMUNICATION protocol provided by Yokogawa. (3) Connect the Arduino with all the working elements including stepper motor, solenoids, IR sensors and. The code will be developed in Arduino IDE.

Week 18-27 (Control Development):

Start the building of a Graphical User Interface on Raspberry Pi in Python. The GUI should provide some users some basic functions, e.g. input desired temperature curve, preview the stop positions of the sample within the transportation range, monitor the real time temperature of the sample, and so on. The tools for developing such GUI include wxPython (a wxWidgets wrapper for python), Matplotlib (to provide a canvas for temperature real time monitoring), MySQL (to record data for later analysis). All above software and tools are open- source, which means they are free in public domain.

Week 28-31 (Testing and Calibration):

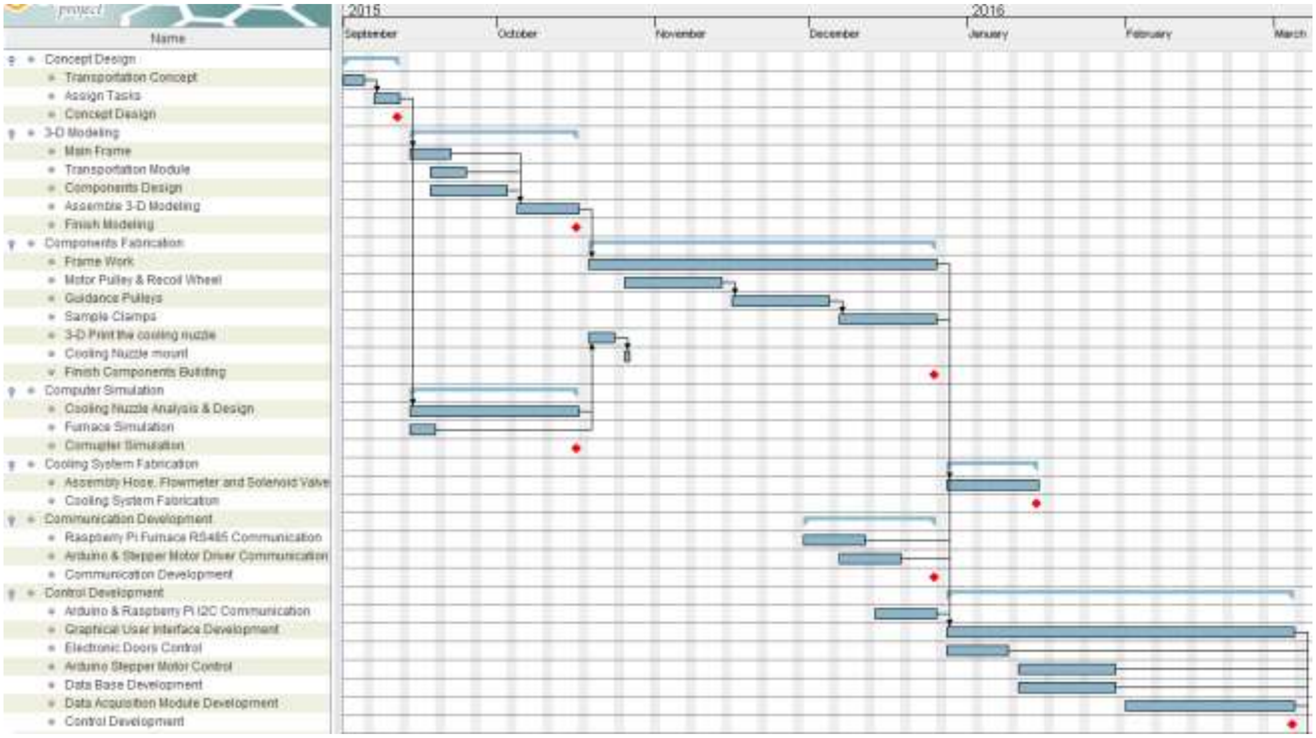
Achieve automatization of all modules, complete control system debug & optimization, and conduct trial operation for adjustment. Make sure the transportation module has high precision of positioning, also test the accuracy and sampling rate of the temperature sensors. **In addition, the proper operation and performance of the CAL-VS1 system has to be calibrated against a well-established system. The laboratory system will be calibrated against the Continuous Annealing Simulator located at the United States Steel Corporation, Research and Technology Center in Munhall. PA. To perform the calibration a series of low carbon steel sheets will be processed using similar thermal cycles in both systems. The microstructural results and analysis of the heating and cooling stages will be compared. Adjustments to the laboratory system will be made, if they are necessary. This calibration stage is essential prior to start working with Advanced High Strength Steels.**

Week 32-46 (Experiments and Validation):

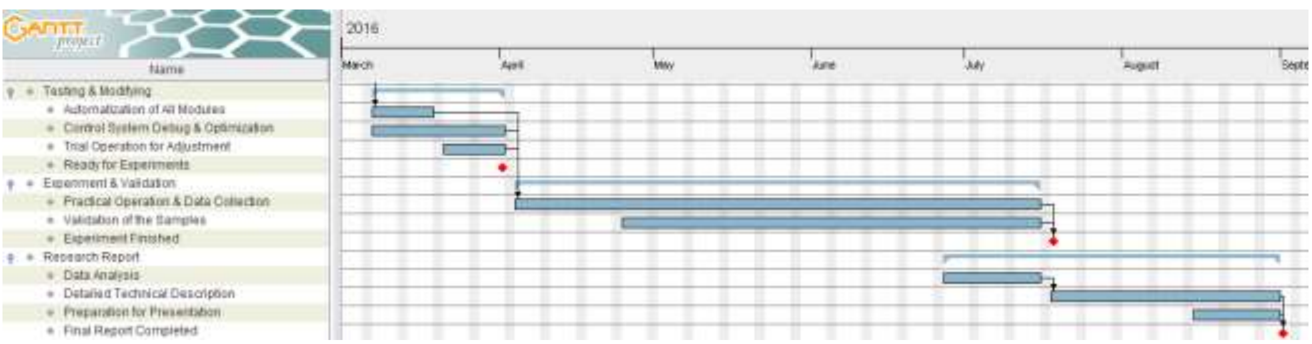
Conduct practical experiments while collecting data, evaluating overall performance of the CAL-VS1 system. Perform material characterization using advanced characterization techniques (SEM-OIM, EBSD-IQ and Phase balance distribution) on the samples heat treated using the simulator.

Week 47-52 (Final Report):

Analyze the data in the experiments and work on detailed technical description, explain the major algorithms in programming and give flow diagram of all modules. Complete the final report of the project.



Name
2015
2016
September
October
November
December
January
February
March
Concept Design
Transportation Concept
Assign Tasks
Concept Design
3-D Modeling
Main Frame
Transportation Module
Components Design
Assemble 3-D Modeling
Finish Modeling
Components Fabrication
Frame Work
Motor Pulley & Recoil Wheel
Guidance Pulleys
Sample Clamps
3-D Print the cooling nuzzle
Cooling Nuzzle mount
Finish Components Building
Computer Simulation
Cooling Nuzzle Analysis & Design
Furnace Simulation
Comupter Simulation
Cooling System Fabrication
Assembly Hose, Flowmeter and Solenoid Valve
Cooling System Fabrication
Communication Development
Raspberry Pi Furnace RS485 Communication
Arduino & Stepper Motor Driver Communication
Communication Development
Control Development
Arduino & Raspberry Pi I2C Communication
Graphical User Interface Development
Electronic Doors Control
Arduino Stepper Motor Control
Data Base Development
Data Acquisition Module Development
Control Development



GANTT project
Name
2016
March
April
May
June
July
August
Testing & Modifying
Automatization of All Modules
Control System Debug & Optimization
Trial Operation for Adjustment
Ready for Experiments
Experiment & Validation
Practical Operation & Data Collection
Validation of the Samples
Experiment Finished
Research Report
Data Analysis
Detailed Technical Description
Preparation for Presentation
Final Report Completed

10. Estimated Project Cost

	Unit Price	Quantity	Total
Mainframe Construction			
20ft Solid Channel Unistrut	$39.16	6	$234.96
Strut Accessories			$100.00
Furnace Support Plate 16" × 16"	$121.57	3	$364.71
Electric Enclosure 12" × 12"× 6"	$96.39	1	$96.39
Total			$796.06
Sample Positioning & Transportation Module			
Stepper Motor NEMA 23	$250.00	1	$250.00
Holding Fixture Material	$20.00	1	$20.00
Pulley and Recoil Material	$100.00	1	$100.00
High-Strength 301 Stainless Steel Strip 100' × 1" × 0.010"	$111.66	1	$111.66
Total			$481.66
Heat Treatment Module			
Lindberg-Blue M Thermo Scientific Model: TF55030C	$2,204.58	1	$2,204.58
Lindberg/Blue M™ 1200°C Split-Hinge Tube Furnaces Model: HTF55322A	$3,300.00	1	$3,300.00
Thermo Scientific Temperature Controller CC58114PC-1	$3,708.00	1	$3,708.00
Total			$9,212.58
Cooling System Module			
Pack of 1FullCure 705 Supporting Resin 3.6KG	$468.00	1	$468.00
Pack of 1 RGD720, 3.6KG Model Resin	$842.00	1	$842.00
291 cubic foot Helium Tank (gas only)	$209.00	1	$209.00
Gas connection tube, hoses and fittings			$70.00
Total			$1,519.00
Electronic Gates Module			
McMaster-Carr Linear Solenoids 12V DC Continuous Duty	$23.68	6	$142.08
McMaster-Carr 303 Stainless Steel Tight-Tolerance Sheet 6" × 6"× 3/8"	$135.65	1	$135.65
McMaster-Carr Structural Fiberglass Fire Retardant 24" × 24" × 1/8"	$48.67	1	$48.67
Total			$326.40
Temperature Detection Module			
Process Sensors™ IR sensor Model: Sirius SI23	$2,550.00	1	$2,550.00

with a Optical Lens OS09-E			
5 Interface Meter Cable	$215.00	1	$215.00
Process Sensors™ IR sensor Model: PSC-G42N with a Optical Lens OPTIC 210	$1,375.00	1	$1,375.00
2.7V 8-Channel 12-Bit A/D Converter MCP3208	$2.63	1	$2.63
Total			$4,142.63
System Control Module			
Raspberry Pi 2, Model B	$46.00	1	$46.00
Arduino Uno R3	$30.00	1	$30.00
Stepper Motor Driver	$60.00	1	$60.00
8-Channel Relay and 24v PSU	$70.00	1	$70.00
ViewSonic VX2252MH 22-Inch LED-Lit LCD Monitor	$132.56	1	$132.56
AmazonBasics Mouse&Keyboard	$13.49	1	$13.49
StarTech 6-Feet DB9 Cable	$6.01	1	$6.01
USB to RS485 / RS422 converter	$29.95	1	$29.95
Lenovo ThinkPad Laptop T450 Ultrabook	$839.00	1	$839.00
Total			$1,227.01

Total Cost (Estimated) of equipment and materials: $17,705.34
Faculty and Students support: $22,801.00
Two graduate students (4 months)……$8,000

One undergraduate student (12 months) …..$ 7,801

One undergraduate student (3 months) ……$2,000

11. Students Involvement

Siwei Peng: chief duties for the modules of sample positioning, heat treatment, electronic gates, temperature detecting and control system, while selecting and assembling devices.

Ruifeng Zhang: in charge of building database and designing electronic gates, involved in 3-D modeling and adjustment of the framework.

Daniel Dulaney: responsible for the cooling system module including design of the cooling nozzle, simulation & optimization, and gas supply & regulator.

Louis B Kish: validation of the samples including microstructure analysis, phase identification, and evaluation of the experiment system.

12. Project Benefit

Several benefits are expected from the proposed project:

1) To provide an educational and training experience to graduate and undergraduate students in the design of a system that involves a multidisciplinary engineering areas;

2) To introduce students to the study of steel systems that are of great interest to the industry;

3) To provide an opportunity for the involved students to use fundamental and applied engineering principles;

4) To educate the engineers of the future.

In addition to these direct benefits by the students, future collaborative research with the steel industry will be enhanced by the creation of a powerful and versatile annealing facility that is specifically suited for the study of Advance Higher Strength Steels for automotive structural applications.