Characterization of Residual Stress During the Manufacturing of One-Inch Steel Coil

Student Researchers: Brian Kadowaki, Andrea Love, Garrett Wass, Haojie Xie
Faculty Advisor: David Johnson • Industrial Sponsor: David Mix with United States Steel Corporation

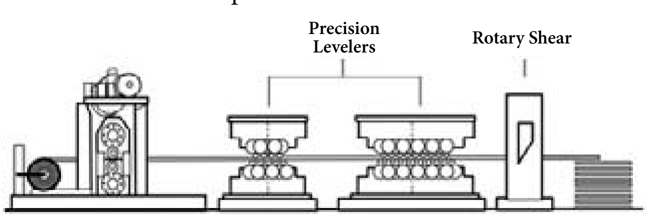
TO CREATE STRUCTURAL COMPONENTS for boom cranes, steel manufacturers need the capability to process one-inch steel coil. Residual stresses present in thick steel coil are due to the larger amounts of constraining material. When the coil is leveled and laser cut into parts, material under residual stress can become unconstrained and warp. Warped steel parts cannot be sold and will damage laser cutting equipment. The manufacturing process was analyzed to locate the cause of residual stresses and investigate residual stress testing methods.

The following is an adaptation of the students' research poster.

Project Background

Grade 50 steel is a high strength low alloy steel. Due to the high yield strength, it is typically used for structural components, trucks, cars, cranes, or roller coasters. Grade 50 steel coils manufactured at U.S. Steel are sent to a company called Steel Warehouse in South Bend, Indiana where they are further processed.

At Steel Warehouse, the coil is sent through a temper mill and then is leveled. After leveling, the now flat steel is sheared into sheets. The crane parts are cut from the sheets with a laser.



Schematic showing an overview of the leveling and tempering process similar to process used at Steel Warehouse.

Goal

The goal of the project is to identify the root causes of the residual stresses manifesting in the Grade 50 1" gauge steel coil and investigate testing to detect warping before laser cutting.

Process Analysis

Thermal relaxation of residual stresses affects the coil after it has been quenched. The Zener-Wert-Avrami (ZWA) equation estimates a normalized quantity of residual stress remaining after a heat treatment of temperature T_a and duration of time t_a.

$$\frac{\sigma^{RS}_{T,t}}{\sigma^{RS}_{293K}} = \exp\left(-\left(C \exp\left(-\frac{\Delta H}{kT_a}\right) t_a\right)^m\right)$$

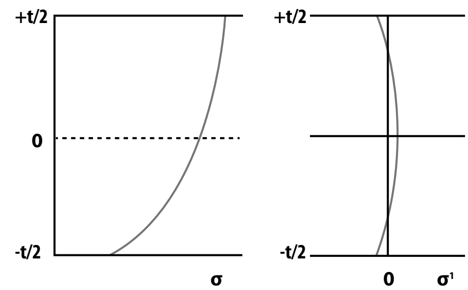
$$\sum_{i=0hr}^{8hr} \frac{\sigma^{RS}_{T(i),1hr}}{\sigma^{RS}_{273K}} = 0.0214$$

ΔH = activation energy for stress relaxation*
k = Boltzmann Constant
C = material-based constant*
m = process-based constant*

* calculated with experimental values from similar steels

Zener-Wert-Avrami equation with definition of terms. Knowing the coil's initial temperature and cooling rate (T_a), the ZWA equation was used to calculate 2.14% remaining residual stresses after 8 one hour iterations (t_a=1 hr). Nikitin, I., & Besel, M. (n.d.). Residual stress relaxation of deep-rolled austenitic steel. Scripta Materialia, 239-242.

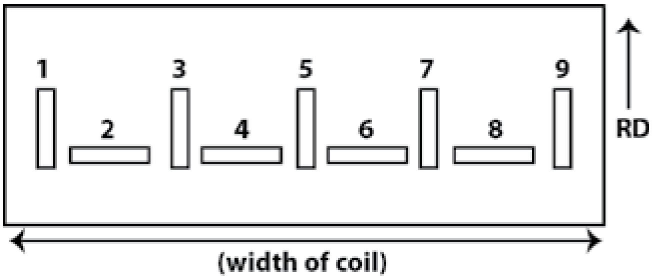
As the steel is uncoiled, a reduction in thickness adds a 1-2% strain along the rolling direction during a tempering pass. This process uses superimposed tension to eliminate residual stress. This is done by pulling the coil in tension to eliminate the neutral axis in the plate.



(Left) stress distribution for bending after super-imposed tension. (Right) Residual stress after super-imposed tension.

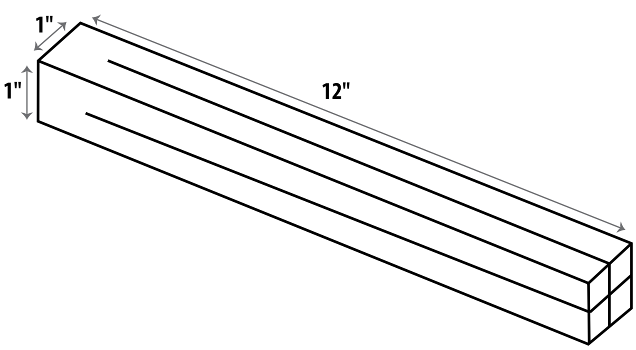
Experimental Procedure

Steel Warehouse has devised a residual stress test called the McNally test. 1" x 1" x 12" samples are cut in both the transverse and rolling directions. The samples labeled with odd numbers are oriented in the rolling direction, and the even labeled samples are oriented in the transverse direction.



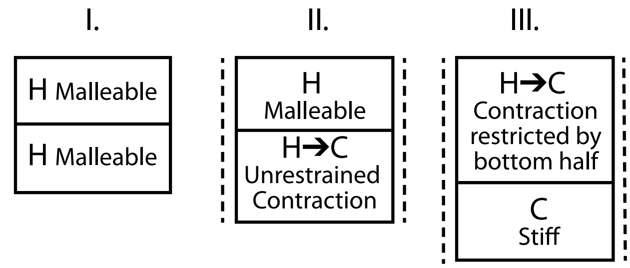
View of steel coil showing the position of the cuts used in the McNally Test.

The sample bar is cut through the thickness and width to measure deflection. An observation in deflection signifies a release of residual stresses. Little vertical deflection was observed and most was in the horizontal plane.



Dimensions of the McNally Test bar. Darker lines signify location of cuts.

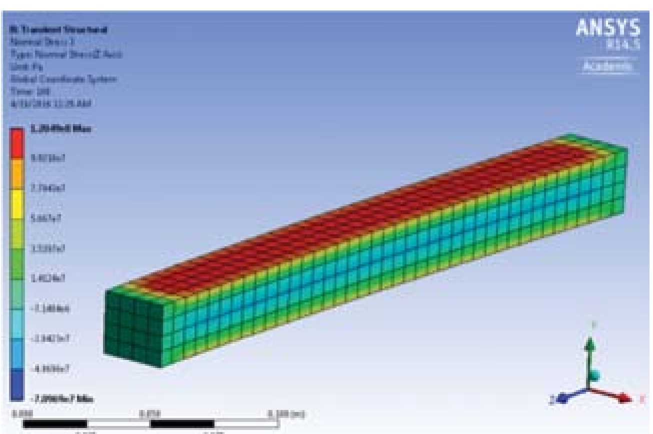
Steel Warehouse uses the McNally test's deflection as a means of detecting residual stress rather than measuring it. Experiments were performed in order to use the deflection of the McNally test to calculate residual stress in a sample. First, residual stresses needed to be imparted to test samples in a known amount through a controlled experiment. The selected method involved heating a 1"x1"x12" sample bar in a furnace to a known temperature. When the bar was fully heated, it was removed from the furnace, and one of the 1"x12" faces was placed in a shallow pool of water for a known time. The cooling from this face introduced a thermal gradient in the bar, which imparted residual stress to the sample through means of thermal expansion and contraction. Thermocouples were used to measure the temperature gradient as the bar cooled. When the bar was fully cooled, it was cut as if it were a McNally test bar, parallel to the plane of the cooled surface.



Stages of imparting a material with residual stress by use of a temperature gradient. A sample begins with both sections hot (H). When the bottom section is cooled (C), it undergoes thermal contraction and pulls the malleable hot upper section with it. When the upper section cools later, it contracts and is resisted by the cold stiff bottom section, placing the material into a residual stress state of compression in the lower section and tension in the upper section.

Simulations

Using the ANSYS finite element modeling software, and transient temperature data obtained from the thermocouples, simulations modeling the cooling experiments were performed to obtain residual stress profiles through the sample.



ANSYS simulation of sample bar heated to 500˚C and cooled on bottom face constantly at 100˚C to induce residual stress.

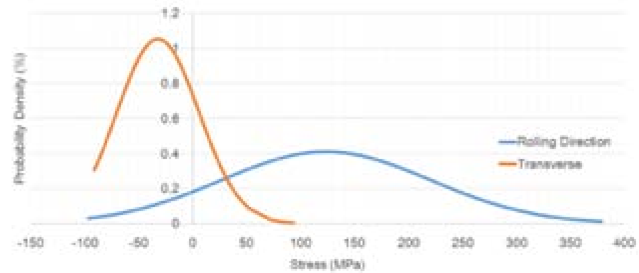
Results and Discussion

Residual stress was calculated based on the deflection data from Steel Warehouse using the equation below. This equation was derived from the bending moment model.

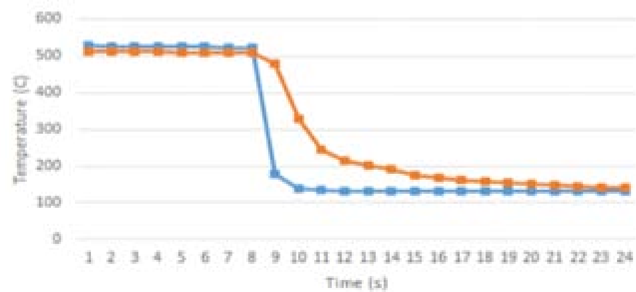
$$\sigma = \frac{3Etd}{4L^2} \quad [1]$$

σ = Residual Stress
E = Young Modulus
d = deflection
L = cut length
t = thickness of the testing bar

The data from the McNally Test at Steel Warehouse is analyzed. Tukey's range test is done to check the statistical significance of residual stress at the different positions along



Normal distribution of residual stress along the rolling (orange) and transverse (blue) direction. Stress in rolling direction is greater than in the transverse direction on average.



Cooling data for sample in one sided cooling test at 600˚C.

the both transverse and longitudinal direction. A normal distribution of data is approximated to check stress different along the two directions. Though there is no statistical stress difference of sample bars along the same direction, the stress in transverse is much different from the rolling direction.

TABLE 1. Residual stress amounts were measured by slitting samples in half lengthwise. Equation 1 (page 38) gave the residual stress. Negative values for lengths indicate an inward deflection.

Heating Temp (˚C)	Top Deflect-ion (mm)	Bottom Deflect-ion (mm)	t (mm)	E (Pa)	L (mm)	Top Stress (MPa)	Top Stress (psi)	Bottom Stress (MPa)	Heating Temp (˚C)
200	0	0	24.71	2×10^{11}	159	0	0	0	0
300	-0.011	-0.0086	26.06			-1.9	-268.4	-1.9	-268.4
400	-0.13	-0.095	25.12			-19.6	-2846.3	-19.6	-2846.3
500	-0.18	-0.14	25.93			29.5	-4273.6	-29.5	-4273.6
600	-0.72	-0.54	26.44			-118.3	-17158.3	-118.3	-17158.3

Recommendations

A large contribution to the residual stresses causing warping can be attributed to the temper pass. The statistical analysis shows that multiple test specimens from the same orientation are not necessary. Therefore, the number of test samples can be reduced to decrease the duration of testing.

For More Information

Companies interested in utilizing the research capabilities of Purdue Materials Engineering should contact Dr. David Bahr at dfbahr@purdue.edu or (765) 494-4100.