Investigation of Triangular Heats Applied to Mild Steel Plates

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HEAT CURVING or heat straightening is at the present time more an art than a science. Prediction of the effects from heating a structural member for the purpose of creating a change in shape is at best a trial and error procedure. Beyond this, the actual internal stresses (residual stresses) have not been measured for specimens in which heat-curving has been the prime objective.

In this investigation, triangular heats were applied to flat plates and the induced curvature measured. Following this, the theoretical curvatures and the associated residual stresses were calculated using an electronic computer. In keeping with standard practical procedures, prior to the application of the heat curving process a preload was applied to the plate. In all cases, this preload induced a known bending stress of 25% of yield at the test section. Finally, tensile test coupons were tested before and after heating in order to determine if there were any significant changes in the yield strength, ultimate strength, fracture stress, modulus of elasticity, and percentage elongation.

TEST PROCEDURE

All tests were carried out on ASTM A36 steel plates initially 6 in. wide by ⅜-in. thick. The edges of these plates were milled so that they were straight and parallel, thus reducing the plate width to 5.9 in. In all, 21 vee-heats were applied and analyzed. The size of the vee-heats varied in both height and width. Each plate contained vee-heats with apex angles of 24°, 30°, 36°, 42°, 48°, 54°, and 60°. The depth of vee-heats, however, varied from plate to plate, but was constant for any one plate. The three depths investigated were:

(1) Half depth (2.95 in.)
(2) Three-quarter depth (4.425 in.)
(3) Full depth (5.9 in.)

Figure 1 illustrates the vee-heat layout on each plate. A loading jig was constructed to hold the test plate steady during the heating operation, and the preload was exerted by a 490 lb weight applied 40 in. from the test section.

Heat was applied on one side of the plate only, using a single orifice oxyacetylene torch. The maximum plate temperature allowed was 1200° F.[1] Beyond this temperature, mild steel begins to show metallurgical transformations which may adversely affect material performance.

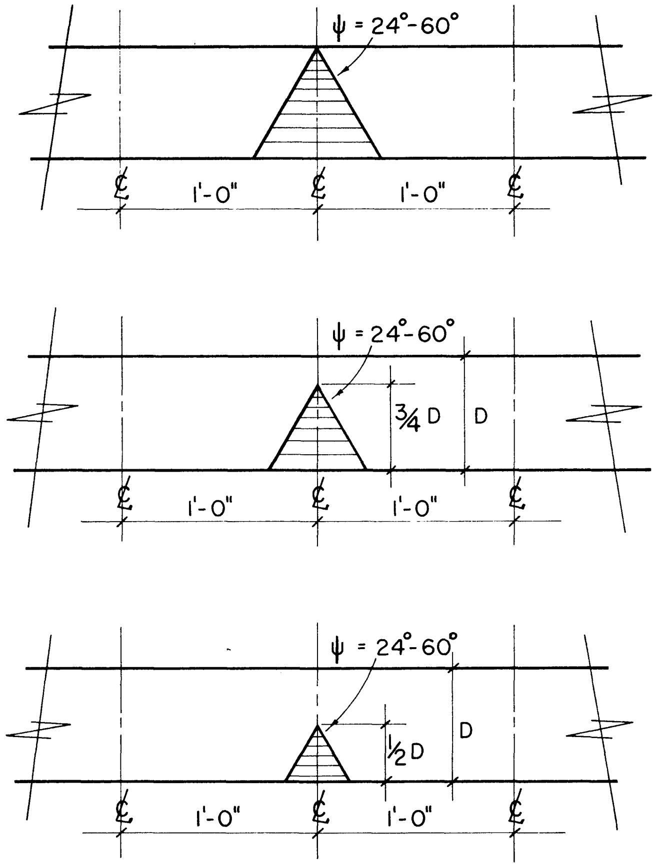

Fig. 1. Vee-heat dimensions

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As shown in Fig. 2(a), the heating was applied in a serpentine fashion starting at the apex of the vee. Determination of the actual temperature in the steel was done by using Tempil sticks. Figures 2(b) and 2(c) show the resulting shape of the plate due to the initial heating, then final cooling. This change in shape from the initial to the final stages results from permanent deformation induced due to the restricted expansion of the heated sections of the plate.

Before heating, tensile specimens were taken from each of the three plates in order to determine yield stress, modulus of elasticity, ultimate stress, fracture stress, and elongation. After completion of the testing program, further tensile coupons were removed from the heated zones, and these same properties were measured again and compared with those from the unheated specimens.

THEORETICAL INVESTIGATION

For the purpose of this investigation, the stress-strain characteristics of the A36 steel were assumed to be perfectly elasto-plastic. This assumption implies that plastic flow takes place at a stress equal to the yield stress. Mathematically, this may be stated as follows:

$$\sigma_r = \min \begin{bmatrix} E \cdot \epsilon + \sigma_i \\ \sigma_y \end{bmatrix}$$

where

σ_r = final stress in the steel
E = Young's modulus
ϵ = increase in strain from equilibrium
σ_i = initial stress in steel
σ_y = yield stress

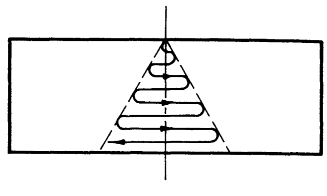
and the resulting strain ϵ_r may be written as

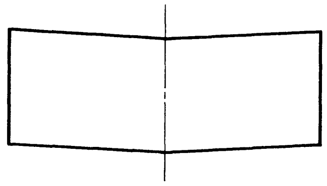
$$\epsilon_r = \epsilon + \epsilon_i$$

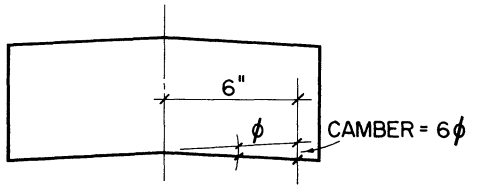
where

ϵ_r = final strain in the steel
ϵ_i = initial strain in the steel

In attempting to analyze the stresses and strains induced in the heated plate, it must be clearly recognized that the previous stress history of the specimen plays an important role. Determination of the camber and residual stresses must therefore take into account the existing stresses in the specimen prior to heating. Since this variation in the existing residual stress is not readily obtainable in most cases, and in order to make the proposed theoretical procedure more generally applicable, the accepted residual stress pattern shown in Fig. 3 was used. The results obtained seem to indicate that this is a reasonable assumption; however, quite possibly some error has been induced here. The computation of stresses and strains can now proceed using the usually accepted criteria.


(A) HEATING PATTERN


(B) SHAPE OF HOT PLATE



(C) FINAL SHAPE OF COLD PLATE

Fig. 2. Camber due to heating

Initially, consider a strip of steel subjected to a temperature increase ΔT. This will create an increase in strain in the heated portions of the strip of

$$\epsilon_T = \alpha \cdot \Delta T$$

where α = coefficient of thermal expansion. This in, crease in strain does not have a stress associated with it- provided the metal is allowed to expand freely. If free expansion is restricted, then there are stresses induced.

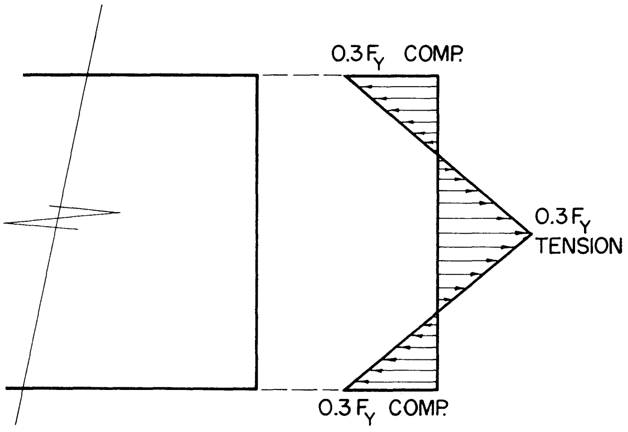


Fig. 3. Initial residual stress distribution

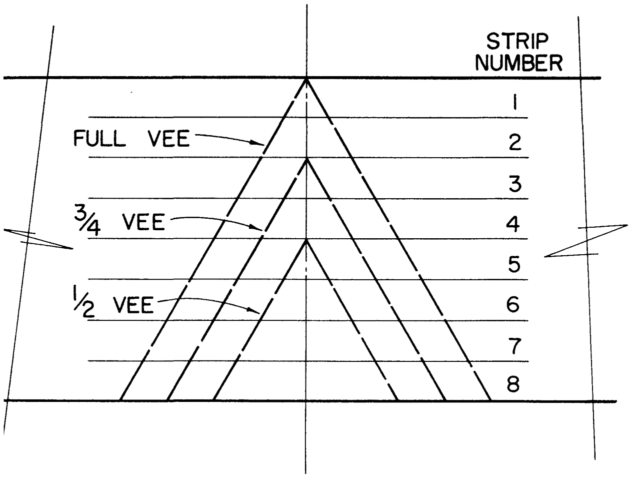


Fig. 4. Location of strips for mathematical analysis

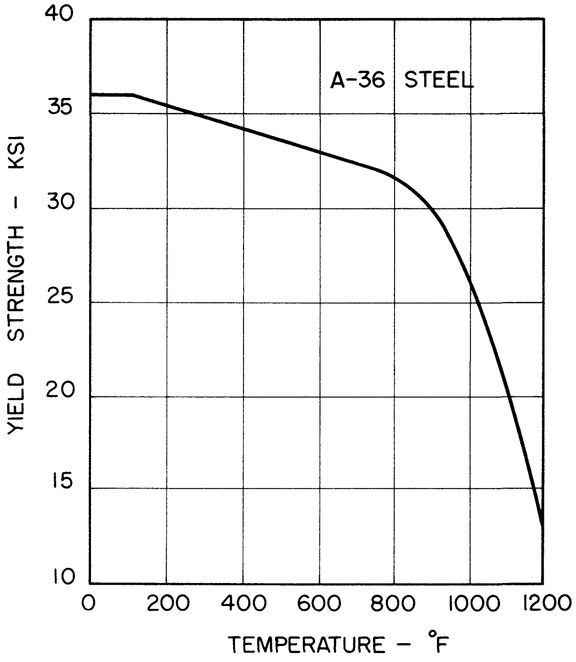


Fig. 6. Variation in yield strength with temperature

In order to simplify the approach to the problem of eating a plate, strip analogy was applied. The vee-eats were considered as eight longitudinal strips varyıg in length as shown in Fig. 4. Here the application of ıe strip analysis inherently assumes that any lateral rains have an insignificant effect on the longitudinal resses. From a comparison of the observed and calcuıted cambers, this assumption appears to be reasonable. ı applying this type of analysis to a heated plate, a nowledge of the material characteristics as a function f temperature is essential. The functions used for this purpose are given in Figs. 5 through 7. The theoretical problem now becomes: For a known static temperature distribution and known thermal characteristics of the material, determine a set of stresses which will create an equilibrium condition in the plate.

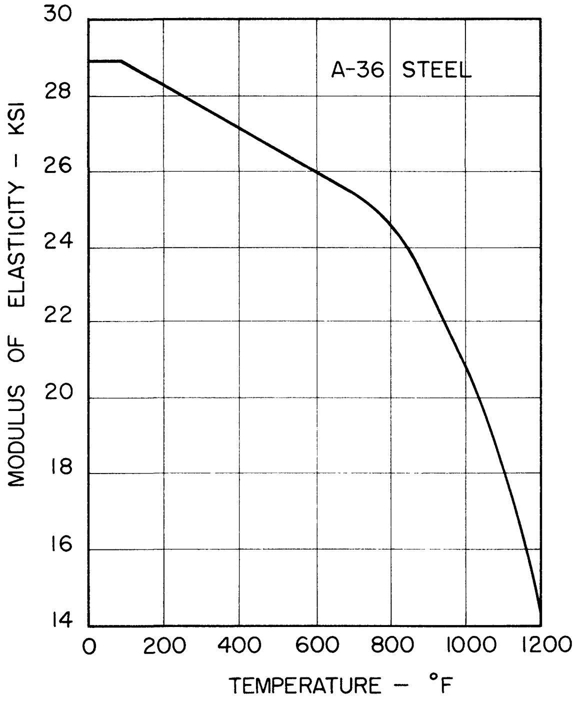


Fig. 5. Variation in modulus of elasticity with temperature

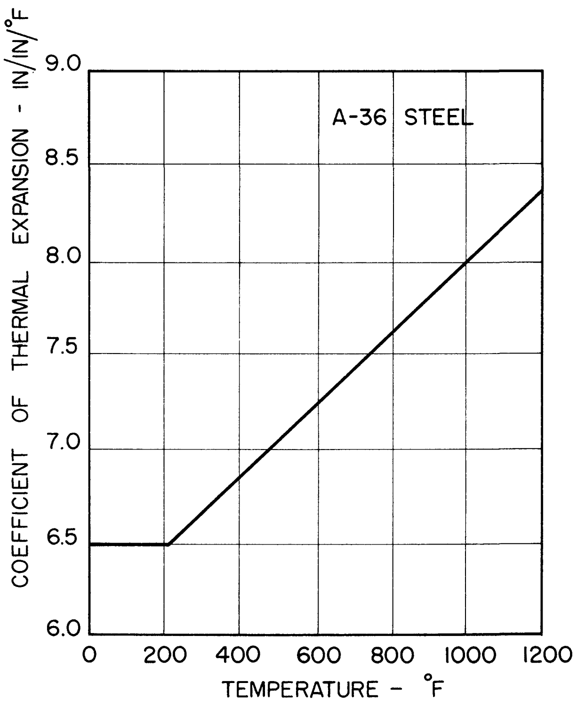


Fig. 7 Variation in coefficient of thermal expansion with temperature

Table 1. Theoretical and Experimental Results

Vee-Heat Apex Angle, Ψ	Theoretical Camber	Experimental Camber
	Full Depth Heats	
60	0.0230	0.0221
54	0.0203	0.0181
48	0.0178	0.0162
42	0.0153	0.0142
36	0.0130	0.0130
30	0.0107	0.0120
24	0.0085	0.0112
	$\frac{3}{4}$ Depth Heats	
60	0.0173	0.0180
54	0.0153	0.0142
48	0.0134	0.0123
42	0.0115	0.0105
36	0.0097	0.0091
30	0.0080	0.0081
24	0.0064	0.0070
	$\frac{1}{2}$ Depth Heats	
60	0.0083	0.0081
54	0.0073	0.0061
48	0.0064	0.0050
42	0.0055	0.0040
36	0.0046	0.0035
30	0.0039	0.0030
24	0.0031	0.0025

Due to the variation in the mechanical properties with temperature as well as the effects of yielding and initial residual stresses, a direct solution was complicated. Thus a trial and error procedure was used. Essentially this trial procedure involved the preselection of a linear strain distribution across the width of the plate for any given static temperature distribution. From this preselected strain distribution, stresses were calculated and these in turn were checked for equilibrium. If equilibrium was not satisfied, additional trials were performed until such time as equilibrium was satisfied for the specific temperature distribution being investigated. By incrementing the temperature distribution after equilibrium had been satisfied, additional trials were carried out until the final ambient temperature distribution was reached. This temperature incrementation followed the heating process actually carried out on the plates.

For the vee-heats investigated, eight temperature distributions were investigated. For each, the resulting stress and strain distributions for the equilibrium configuration became the input values for the next trial in the procedure until the final steady state temperature was reached. The final residual strains obtained were used to compute the camber induced in the plate.

Table 2. Mechanical Properties Before and After Heat Curving

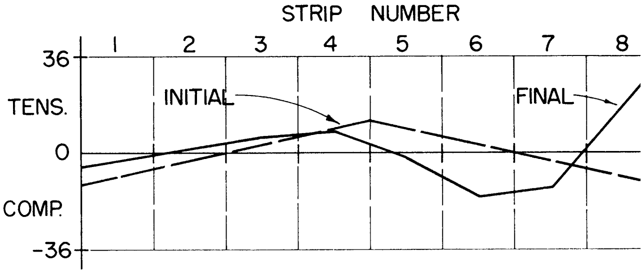
Property	Before Heating	After Heating
Yield strength	36 ksi	37 ksi
Ultimate strength	67 ksi	70.3 ksi
Fracture stress	44.2 ksi	48.6 ksi
Modulus of elasticity	28,970 ksi	29,000 ksi
Elongation[a]	40%	30%

[a] 2-in. gage lengths.

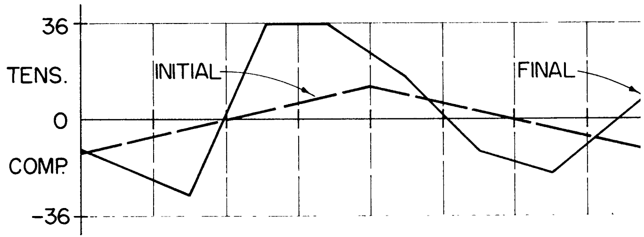
RESULTS AND DISCUSSION

A comparison of the resulting theoretical cambers wit those from experiment are given in Table 1. Here th camber values given for comparison are defined in Fi 2(c).

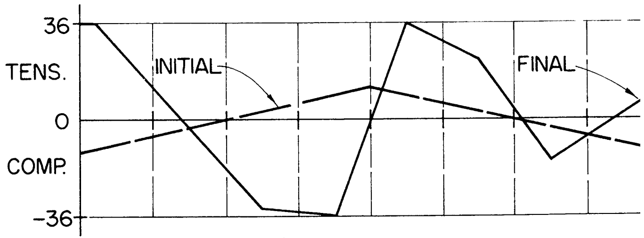
Tensile coupons of the original unheated and fin heated sections were tested to failure to measure an changes in yield strength, ultimate strength, fractur stress, modulus of elasticity, and elongation. Table gives the results of these tests.



(A) FULL DEPTH



(B) $\frac{3}{4}$ DEPTH



(C) $\frac{1}{2}$ DEPTH

Fig. 8. Initial and final residual stresses in ksi

The theoretical computations predicted not only camber but also residual strains and residual stresses. On the basis of the comparisons given in Table 1, the residual stress distributions given in Fig. 8 are felt to be reasonably accurate.

Table 1 indicates that the theoretical approach has very closely predicted the values determined by experiment. There are several places in the theoretical analysis where large errors may be incorporated, and these are listed below:

(1) Distribution of initial residual stresses.
(2) Assumed linear strain distribution for analysis.
(3) Control of temperatures in plate during heating.
(4) Effective heated area.

The residual stress distribution assumed in this report is nominally accepted in practice. From a theoretical point of view, this distribution becomes very important since variations here can induce error. It is therefore very significant that the cambers predicted by experiment can be plotted on a smooth curve for each separate depth of vee-heat.

The assumed linear strain distribution used to predict the equilibrium configurations in the theoretical analysis could be generalized to a higher order algebraic expression. This type of higher order strain distribution could only be predicted by experiment.

Although the region heated was a vee, the thermal conduction of steel is high enough that significant temperatures could have been reached outside this area. This being the case, the heated region adjacent to the vee-section could affect the camber. The mathematical computations used to compute the theoretical camber were found to be dependent upon the temperature distribution. For this purpose, a reasonably accurate determination of this temperature distribution at any time is necessary for the accurate determination of the theoretical cambers.

CONCLUSIONS

The theoretical and experimental camber values are in reasonable agreement, which indicates that the theoretical approach can be used to predict actual cambers to be expected in practice. Further justification may be necessary, however, in the case of rolled structural members or welded sections. In the latter case, the additional stresses due to welding must be known in order to apply the analytical procedure.

Using the allowed maximum temperature, the change in mechanical properties appears to be very small for all vee-heat depths.

The distribution and magnitude of the final residual stresses indicate the desirability of using the full depth rather than the three-quarter or half depth vee-heats.

ACKNOWLEDGMENTS

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