A Weldability Testing Procedure for Premium Rail Steels with Reference to V-N Steels

A procedure for determining electroflash welding parameters is developed and successfully applied to the welding of Cr-Mo premium rails

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ABSTRACT. A weldability testing procedure for premium rail steels has been developed in which simulated electroflash welds were made from various V-N experimental rail steels in a Gleeble apparatus using 10 × 10 × 75 mm (0.39 × 0.39 × 3.0 in.) samples. A fairly wide range of cooling rates produced pearlitic structures. The hardness distributions in the simulated weld part of the samples were almost uniform, showing that the V-N rail steels have good electroflash weldability.

A procedure for determining electroflash welding parameters is presented. The procedure has been applied to the welding of Cr-Mo premium rails.

Introduction

Possibly the most important feature of an electroflash weld (EFW) is that the weld is a solid-phase weld (SPW) and, therefore, should have no fusion or solidification region within its boundaries, unless the weld is defective. The joint region consists of base metal that has been subjected to a thermal cycle in which peak (or maximum) temperatures ranging from A_1 (720°C or 1328°F) to T_m (1500°C or 2732°F) have occurred.

The object of this paper is to describe a procedure for assessing the weldability of premium rail steels with particular reference to a series of V-N steels. The procedure consists of simulating the thermal conditions which occur during an electroflash weld. The microstructure and the hardness profile of the simulated welds are then examined to determine the weldability of the steel being studied. A procedure for determining electroflash welding parameters has also been developed. In this procedure the structure and cooling rate of simulated welds are compared to the structure and flash-welding parameters of trial flashwelds. By making suitable changes to the flashwelding parameters, as determined from the above comparison, good flashwelds can be obtained.

Simulation of Electroflash Welds

The weldability study under discussion was designed to examine the transformations that take place in solid phase welds of rail steels. To achieve this, steel specimens must be heated to various peak temperatures between 720 and 1500°C (1328 to 2732°F) and then cooled to room temperature at various cooling rates. The Gleeble apparatus is specially suited to produce specimens with the desired thermal histories.

Since the only transformation to be observed when cooling a solid phase weld is the transformation of austenite to its decomposition products, and since the cooling rate from the AC_1 temperature determines the products of the transformation, as shown by continuous cooling transformation (CCT) diagrams, the cooling rate at which the transformation takes place is the critical thermal parameter.

Experimental Procedure

The composition of V-N steels that were tested in these experiments are given in Table 1. To provide the information necessary for the determination of the flash welding characteristics of these steels, dilatometric as well as Gleeble experiments were conducted. The following procedures were, therefore, drawn-up:

1. Standard dilatometer samples (Fig. 1) were machined, and all the critical points were determined by dilatometry even though the main objective was to determine the Ar_3 temperatures—Fig. 2.
2. Samples of each steel were machined to a 10 × 10 × 75 mm (0.39 × 0.39 × 3.0 in.) cross-section. These particular dimensions were selected so that Charpy blanks for conventional or instrumented tests could be prepared if desired.
3. The machined samples were thermally cycled on a Gleeble thermalcycle simulator.[1] The main features of such thermal cycles are shown in Fig. 3; a maximum peak temperature of 1000°C (1832°F) was used.

Results and Discussion

The results of the dilatometric experiments are shown in Table 2. Since the critical temperatures are the same within experimental error, the results from the thermal cycling experiments to be given below are for steel

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Table 1—Chemical Composition of the V-N Steels Examined in the Present Paper

Rail	Composition, %[a]									
	C	S	P	Si	Mn	Al	Cr	V	Nb	N
G	0.67	0.035	0.023	0.60	1.00	0.020	0.80	–	0.053	–
H	0.71	0.032	0.018	0.58	1.05	0.010	0.77	0.10	0.056	0.014
I	0.70	0.023	0.020	0.63	1.09	0.010	0.81	0.20	0.051	0.020
J	0.72	0.033	0.019	0.27	0.76	0.010	1.27	–	–	–
K	0.72	0.039	0.017	0.30	0.74	0.005	1.36	0.10	–	0.014
L	0.64	0.041	0.016	0.62	1.12	0.005	0.82	0.10	–	0.013
M	0.74	0.038	0.017	0.29	0.75	0.005	1.28	0.19	–	0.016

[a] Residual element levels (%): Sn-0.002; Cu-0.01/0.02; Ni < 0.005/0.03, Mo < 0.005/0.07.

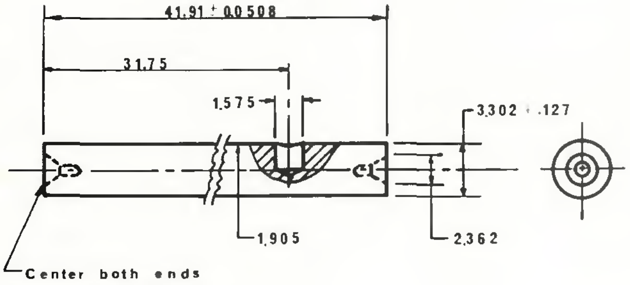

Fig. 1—Dilatometer bar

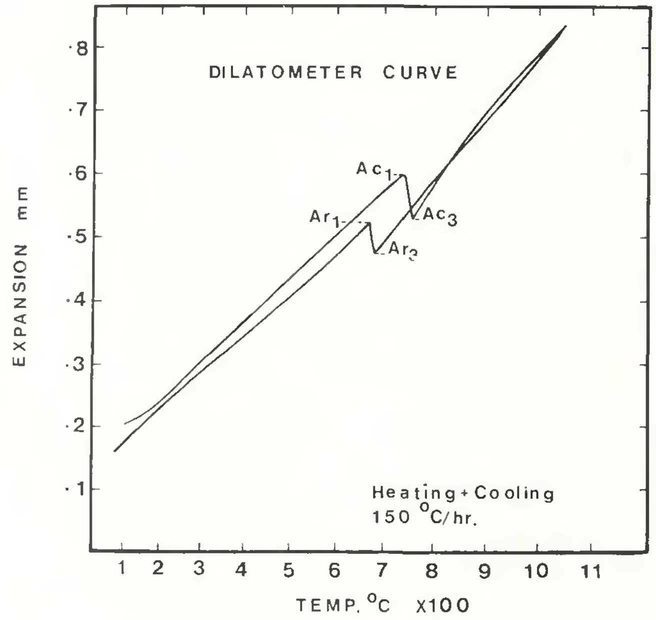

Fig. 2—Dilatometer curve for rail steel H

H unless otherwise specified.

The etched Gleeble specimens were similar in appearance to the sample shown in Fig. 4. The central part of the bar, about 10 mm (0.39 in.) in length, had a different etching behavior to the rest of the bar, because it had transformed into austenite during thermal cycling. The peak surface temperature measured at the Gleeble control thermocouple was about 1000°C (1832°F); however, the peak temperature in an electroflash weld is close to the melting point of steel.

An etched sample machined from an electroflash weld is also shown in Fig. 4. Again, the dark-etching region is bounded by two planes whose peak temperature was Ac_1, or roughly 720°C (1328°F) depending on the composition of the steel. This region closely resembles the similar region for the Gleeble bar, shown in Fig. 4, except for the slant in the Ac_1 plane caused by the complex geometry of the rail section. These boundary planes are identical to the outside outline of the heat-affected zone of a fusion weld.

A special jig was designed and built to determine the hardness vs. position data for thermally cycled as well as flash-welded bars—Fig. 5. The results of hardness surveys on three samples of steel H, each thermally cycled at a different cooling rate, are shown in Fig. 6.

The hardness of the base metal, the highest and lowest hardnesses of the simulated welds, and the cooling rates for several V-N steels are given in Table 3. Since all the hardness values are within the acceptable range of 30-40 Rc, a weld cooling rate of about 1°C/s (1.8°F/s) would give satisfactory weld hardnesses for these steels.

A macrograph together with microstructures from various locations of a

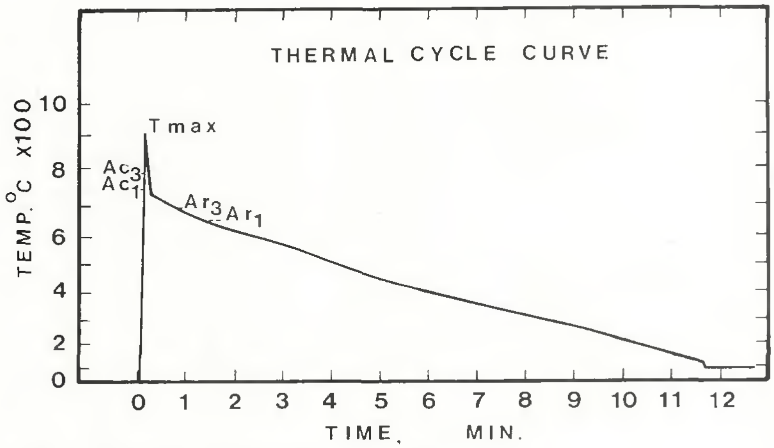

Fig. 3—Thermal cycle curve for rail steel H

Table 2—The Critical Temperatures[a] for a Number of V-N Steels

Rail	Critical temperature[b]			
	Ac_1 α	Ac_3 γ	Ar_3 γ	Ar_1 α
G	750	775	690	680
H	755	770	680	670
I	760	775	680	670
J	745	770	680	680
K	750	775	700	675
M	755	780	700	690

[a] Heat and cooling rate—150°C/h (302°F/h).
[b] See Figs. 2 and 3—also note that the meaning of the notation is illustrated in Fig. 2.

Fig. 4—Thermally cycled sample (A) from Gleeble experiments and a Charpy bar machined from a flash welded rail (B). Nital etch. The flash-welded sample is a 1% Cr steel

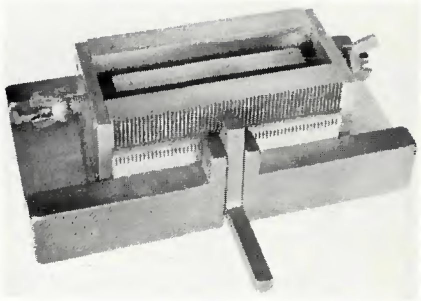

Fig. 5—A jig for measuring hardnesses at fixed positions

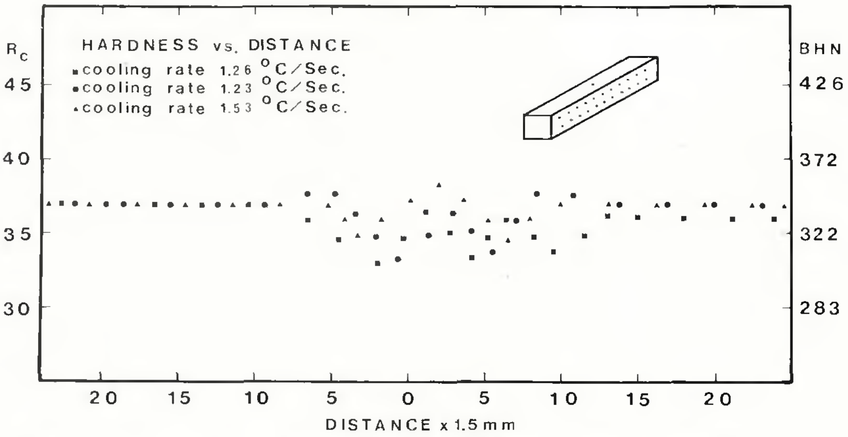

Fig. 6—Hardness vs. distance profiles for three different samples of steel H

Gleeble sample are shown in Fig. 7. The grain size has been greatly refined close to the Ac_1 boundary plane, whereas the grains are coarser closer to the center line of the specimen. The microstructures appear to be completely pearlitic, but the individual cementite plates cannot be resolved by optical microscopy because of the fineness of the structure.

Carbon extraction replicas were taken of the left sample in Fig. 4A to determine if bainite and/or martensite were present. The uniformly pearlitic structures of the base metal are shown in Fig. 8. These microstructures are representative of the structures found in region I of Fig. 7.

The microstructures near the center of the simulated weld were also mainly pearlitic (Fig. 9A), but minor amounts of bainite were also present—Fig. 9B. This bainite is considered to be the cause of the small increase in hardness at the center of the Gleeble samples—Fig. 6. These microstructures are representative of the structures found in region III in Fig. 7.

The above results can be evaluated in several ways. However, for electroflash welding the transformation products and hardness as a function of cooling rate are the important results. Ideally, when welding two rail sections, the objective is a smooth continuation of properties from one section to the other. A quick method of testing for the desired uniformity is a hardness survey—Fig. 6. The plot of hardness vs. distance should be a straight line parellel to the distance axis. This should be almost attainable with the correct thermal cycle.

The results shown in Fig. 6 are representative of the results obtained for V-N steels (also see Table 2). Since the uniformity of the hardness surveys for the V-N steels was good, the steels are considered to have good weldability at cooling rates of about 1°C/s (1.8°F/s).

An interesting outcome of these experiments is the realization that the Gleeble apparatus can be used to determine the range of cooling rates in rail manufacture which will give satisfactory rail properties. Similarly, the Gleeble apparatus can also be used to screen alloys in alloy rail development programs for both conventional and enhanced cooling methods of rail manufacture.

Determination of Flash Welding Parameters

By conducting Gleeble experiments similar to those outlined above, an appropriate cooling rate for the flash-welding of rails can be determined. This cooling rate must be translated into flashwelding parameters in order to produce acceptable flashwelds. Fletcher[3] has also simulated flashwelding using a Gleeble apparatus. However, since few details of his work are

Table 3—Cooling Rates and Resulting Hardness Values for a Number of V-N Experimental Steels

Steel sample	Cooling rate dT/dt, °C/s	Hardness, R_c Base metal	Simulated weld Hardest	Simulated weld Softest
3G	.93	36		30-31
7G	.92	33		30-32
1G	1.21	34	36	32-34
2G	1.39	34-35	40	
4G	1.35	34-35	36-37	32-33
1H[a]	1.26	36-37		33-34
2H[a]	1.23	37	38	34
3H[a]	1.53	36-37	38	33-34
1I	1.31	38	40	36-37
2I	1.24	37-38	38.5	34
3I	1.53	37-38		34-35
4I	1.87	36-37	39-40	
1J	1.33	32-33	36-36.5	
2J	1.21	33-34	36-37	
3J	0.892	32-33	33	31
1K	1.44	36-37		33-34
2K	1.86	36-37	36-36.5	34
3K	1.63	35-36		31
1M	2.0	36-37		34-35
2M	2.32	36-37	37	32-33
5M	2.57	37-38	38-39	34-35

[a] See Fig. 6 for a graph of hardness vs. distance for these steels.

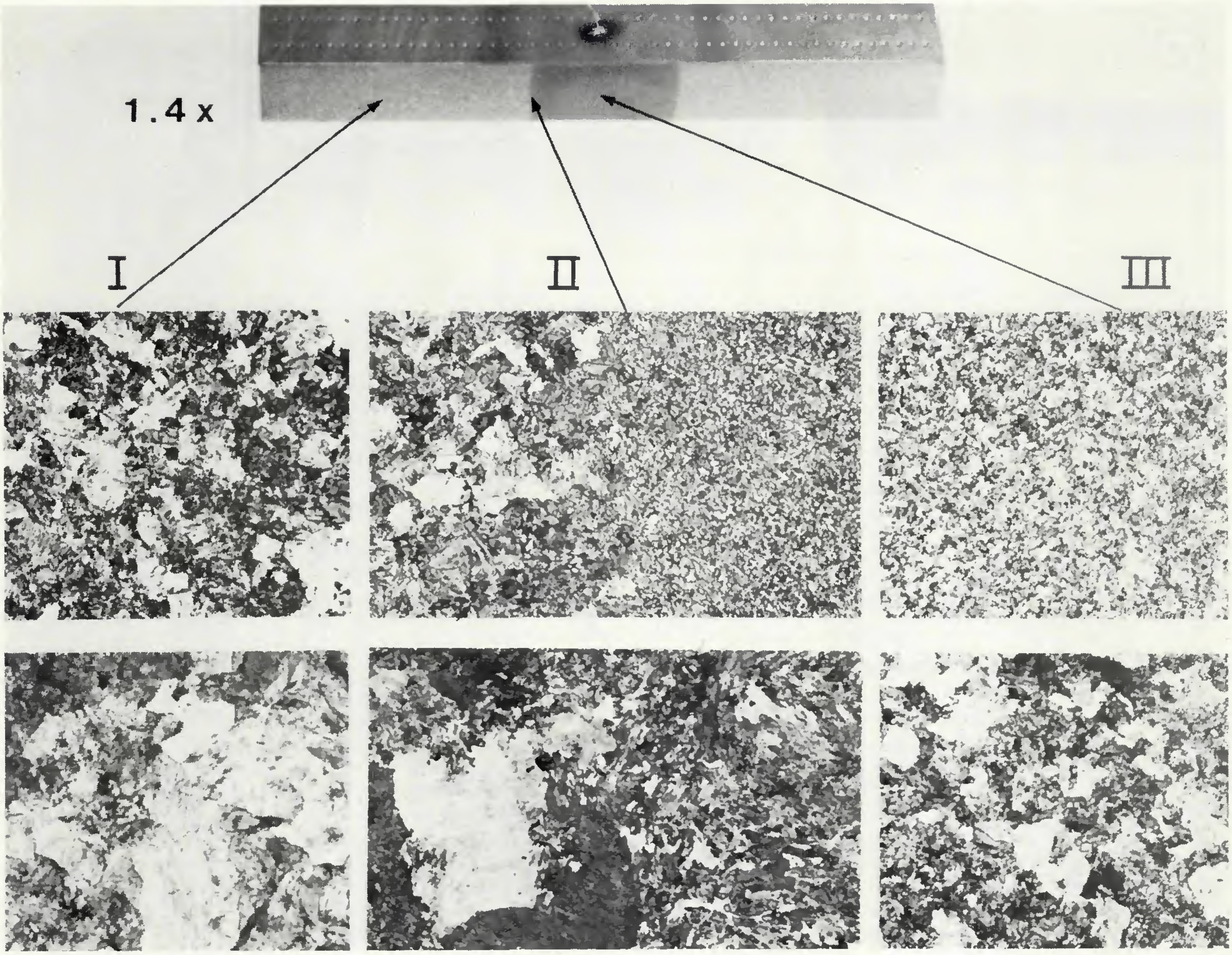

Fig. 7—Macrograph (X1.40) and corresponding micrographs (X1000 and X500) from a Gleeble sample

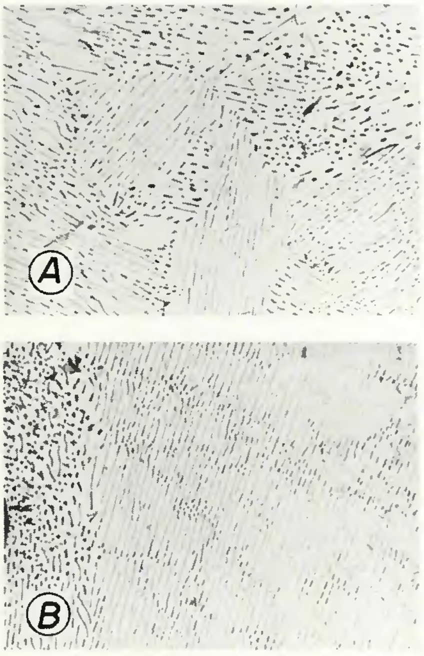

Fig. 8—Uniformly pearlite structure of base metal carbon extraction replicas. X11,200 (reduced 41% on reproduction)

available, no comparison with the present work is possible.

In order to determine optimum flashwelding parameters for a particular alloy, trial flashwelds have to be made. Since recording of temperatures during electroflash welding is not practical at present, the flashwelding parameters must be measured and correlated with the resultant weld hardness profile and microstructure. A schematic example of flashwelding parameters, i.e., the current during preheat, flashing and postheat as well as the movement of the platen, is given in Fig. 10.

Samples of the same rail steel should then be tested at various cooling rates in the Gleeble apparatus in order to determine through similarities in structure and hardness the cooling rate of the flashweld. By subsequent suitable changes in the flashwelding parameters, particularly the postheat cycles, the desired weld cooling rate and structure can be obtained.

The above technique has been applied to the flashwelding of Cr-Mo

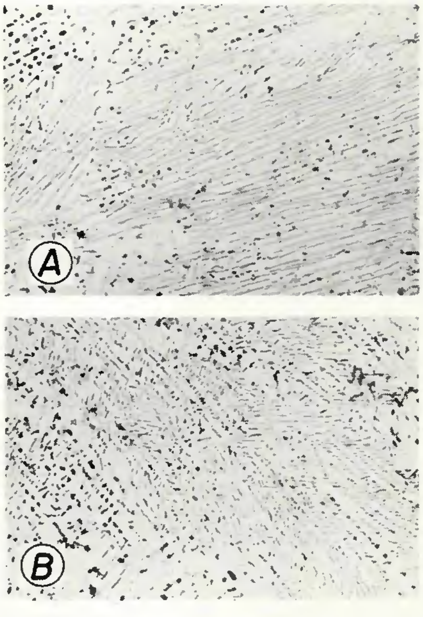

Fig. 9—Microstructures near center of simulated weld: A—pearlitic structure near center line of simulated weld; B—regions of bainite carbon extraction replicas. X11,200 (reduced 41% on reproduction)

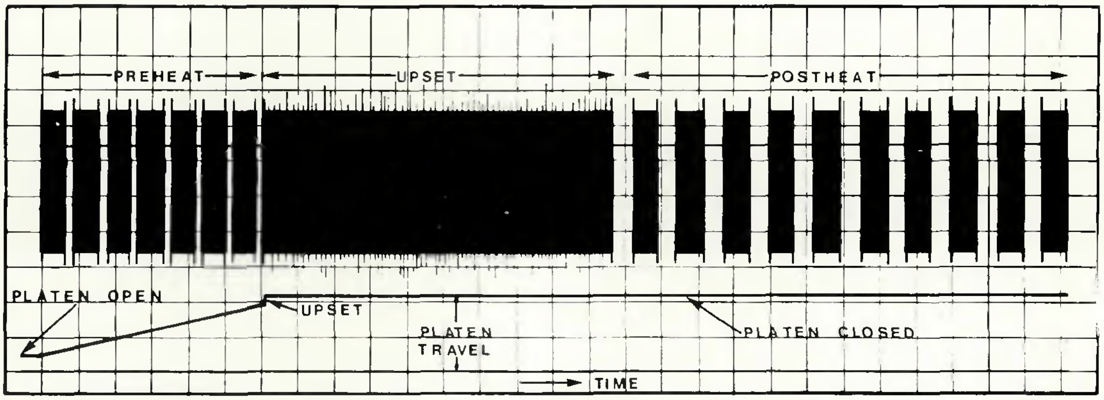

Fig. 10—Schematic for a typical electroflash cycle for an actual weld made on the basis of a preliminary weldability study

alloy rail. Gleeble experiments on this rail showed that at cooling rates up to 0.8°C/s (1.4°F/s), no bainite or martensite was formed in simulated welds. Three samples of flashwelded rail, were obtained together with their flashwelding parameters, were examined for microstructure and hardness.

On the basis of comparisons between the simulated weld properties and cooling rate and the flashweld properties and flashwelding parameters, recommendations were made to the supplier on changes to be made to the flashwelding parameters for Cr-Mo rail. These recommendations proved to be of assistance in determining a suitable flashwelding cycle for the welding of Cr-Mo rails.

Conclusions

1. A procedure has been developed using the Gleeble thermal cycle simulator that determines both the weldability of rail steels and the acceptable range of weld cooling rates.
2. A series of experimental V-N rail steels has been shown to have good weldability using the above procedure.
3. A comparison procedure using simulated welds and actual flashwelds has been developed and reduces the number of flashwelding trials required to determine flashwelding parameters for a given rail steel. This procedure has been of assistance in determining the flashwelding parameters for a Cr-Mo rail.
4. The Gleeble thermal cycle simulator can be used to determine the range of cooling rates for the manufacture of rail from any given alloy.
5. The Gleeble apparatus can be used to screen alloys for both conventional and enhanced cooling methods of rail manufacture.
6. Although cooling rates are the critical parameter in the present study, in practice they are not used because of lack of cooling rate data derived from the EFW. Therefore the EFW and simulated welds are compared with respect to hardness and microstructures.

Acknowledgment

The authors are indebted to Dr. K. Winterton for continuous interest and encouragement.

References

1. Savage, W. F., *App. Polymer Science* 6, 303, 1962.
2. Marich, S., and Curcio, P., Development of high-strength alloyed rail steels suitable for heavy duty applications, Research Report, BHP Melbourne Research Laboratories, June 1976.
3. Fletcher, F. B., Development of a weldable high-strength Cr-Mo rail steel, L-311-12, August 16, 1977.

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