extremely well from the standpoint of hot cracking.

Plate no. 4, however, rated as well as plate no. 5 in the actual welding tests (if not in the cast pin tear study) and enjoys the improvement of impact strength, and equalization of ductility in longitudinal and transverse directions, resulting from cerium treatment.

As for deoxidation, the rare-earth elements are the strongest deoxidizers that can be added to steel and still persist as significant residuals to prevent the formation of undesirable oxides and sulfides in, during or near welding passes. From the standpoint of the steelmaker rather than the fabricator, optimum cerium residuals are obtained by surrounding the teeming stream during casting by an inert atmosphere—so eager are the rare-earth elements to react with oxygen.

Reasonably priced construction steels treated with rare-earth additions are beginning to appear on the market. Accordingly, the phenomena that Baker and Emmanuel have investigated, the welding tests conducted by the latter, and what is known about the benefits of rare-earth elements in welding plate, would all seem to be attaining a significance in welding technology greater than heretofore.

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# Technical Note: Sulfur and Phosphorus in Low Alloy Steel Welds Containing Up to 6% Nickel

BY N. KENYON AND A. L. EPSTEIN

## Introduction

It has been known since at least 1940 that sulfur and phosphorus can promote hot cracking and lower toughness in alloy steel welds.[1] These damaging effects, however, have become particularly evident in recent years with the introduction of weldable steels that are capable of retaining good toughness at high strengths.[2] Investigations of sulfur and phosphorus in welds have usually sought to define the maximum amounts that can be tolerated in an alloy composition of commercial interest. The work described here is somewhat different in that it examines the influences of sulfur and phosphorus as the level of another element—in this case, nickel—is systematically varied.

## Experimental Procedure

### Materials

The filler metals used contained the following nominal levels of nickel, sulfur, and phosphorus: Ni—2%, 4%, and 6%; S—.005%, .010%, and .020%; P—.008%, .015%, and .020%.

They were fully replicated to give $3^3$ or 27 heats. The carbon (0.14%), silicon (0.3%), and manganese (0.9%) levels were held constant for all the heats and were selected as representative for low alloy steel filler metals. The manganese level was also chosen so that the values of the manganese/sulfur ratio would always exceed those normally recommended.

The heats of filler metal were air-melted, deoxidized with silicon and manganese and killed with aluminum. Rods were extracted from each heat into Vycor* tubes and swaged and centerless ground to 0.125 in. diameter for manual gas tungsten-arc welding.

### Base Metal

All the welds were made on $^1/_2$ in. thick plate with the following composition (wt-%): Ni–4.0, C–.13, Mn–.80, Si–.35, S–.007, P–.009 and Fe–balance.

The 4% nickel composition was chosen so that dilution effects from the plate would be kept to a minimum.

The material for the base metal was air-melted, deoxidized with silicon and manganese, and killed with aluminum. The plates were heat treated at 1600° F/1 hr and water quenched.

### Welds

One single vee butt weld, 7 in. long, was made with each filler metal using the manual gas tungsten-arc process and a heat input of approximately 70,000 joules/in.

The joint was filled in 10 passes. The welds were X-radiographed and transverse slices from the welds were polished, etched, and examined at X30 magnification.

The total number of cracks on eight faces was used as an index of the cracking tendencies. A standard circular groove test[2] was also tried as a test for crack susceptibility but proved unsuitable since no cracking occurred even with the most crack-sensitive compositions.

## Results and Discussion

### Effect of Sulfur and Phosphorus on the Incidence of Cracking

The influence of sulfur and phosphorus on weld metal cracking is summarized in Figs. 1 and 2. At con-


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*Trademark of Corning Glass Works.

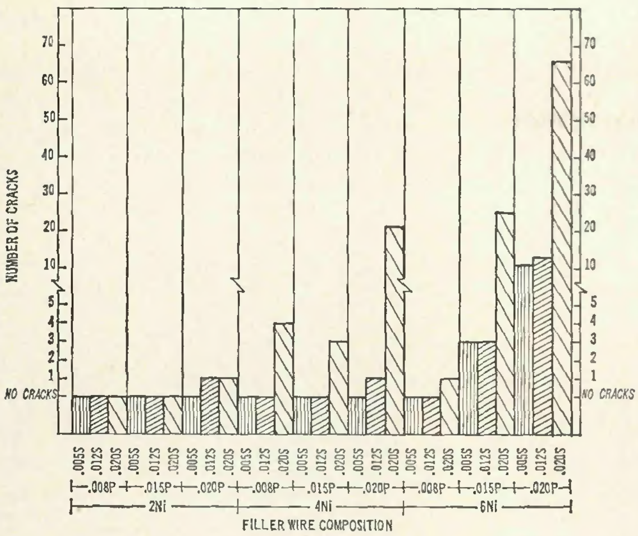


Fig. 1—Effect of filler metal composition on weld cracking. Effect of S at constant P and Ni

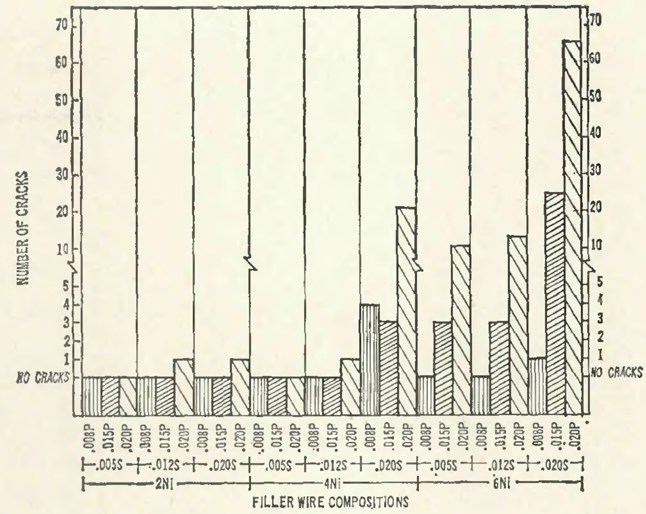


Fig. 2—Effect of filler metal composition on weld cracking. Effect of P at constant S and Ni

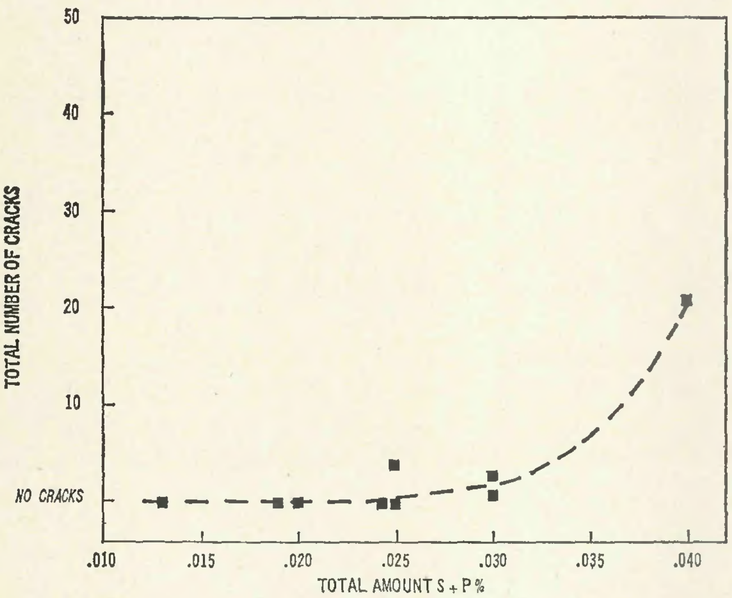


Fig. 3—Number of weld cracks vs. amount of S+ P for the 4% Ni filler metals

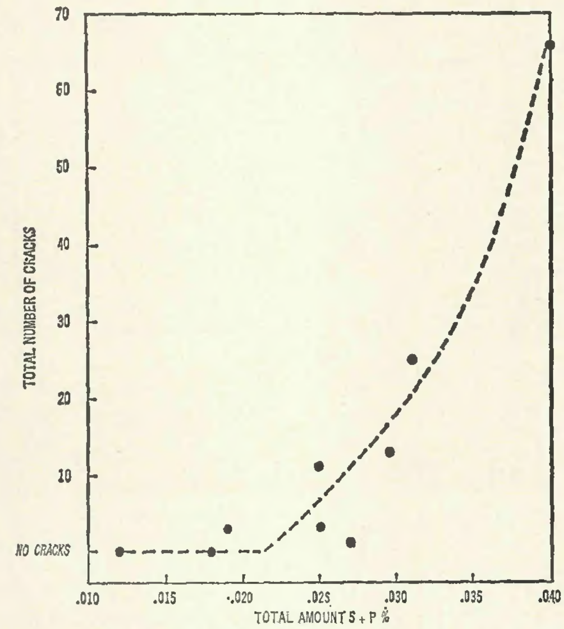


Fig. 4—Number of weld cracks vs. amount of S + P for the 6% Ni filler metals

stant nickel and phosphorus levels, cracking increased as the sulfur level increased, the effect being most pronounced at the higher phosphorus levels—Fig. 1. Very similar trends were seen when the phosphorus level was increased while the nickel and sulfur levels were held constant—Fig. 2. Regression analysis of the number of cracks vs. composition showed that within the range studied, sulfur and phosphorus exerted similar quantitative effects.

At high levels of sulfur and phosphorus the extent of cracking increased with increasing nickel content; but increasing the nickel content had no effect when the amounts of sulfur and phosphorus were low. Crack-free welds were made at the 4% and 6% nickel levels when the combined amounts of sulfur and phosphorus were less than approximately 0.020 to 0.025%—Fig. 3 and 4.

In light of these results, some published comments (see, for example, Lancaster[4] and DMIC Report 172.[5]) that nickel has an adverse effect on cracking appear to be rather arbitrary and perhaps result from observations made some years ago when higher levels of sulfur and phosphorus were more common. The advantages of increased purity are now widely recognized. Moreover, when a combination of high strength and higher toughness is required, low levels of impurity elements such as sulfur and phosphorus, have been shown to be necessary.[2, 6] This is perhaps especially true for filler metals.[7]

Modern refining techniques make these low impurity levels practicable, and .01% maximum for sulfur and phosphorus have proved to be reasonable specifications in high strength, high toughness steels.[2, 6, 7] These levels are now being met in commercial filler metals for low alloy steels with tensile strengths similar to those involved here, i.e., approximately 130 ksi for the 6% nickel level—Fig. 5.

## Conclusions

1. In the low alloy steels examined, sulfur and phosphorus exerted similar quantitative effects in promoting weld cracking.

2. At high levels of sulfur and phosphorus the extent of cracking increased with nickel content, but the nickel content had no effect when the

amounts of sulfur and phosphorus were low.

3. Crack-free welds were made with filler metals containing 6% nickel when the combined amount of sulfur and phosphorus did not exceed approximately 0.020%.

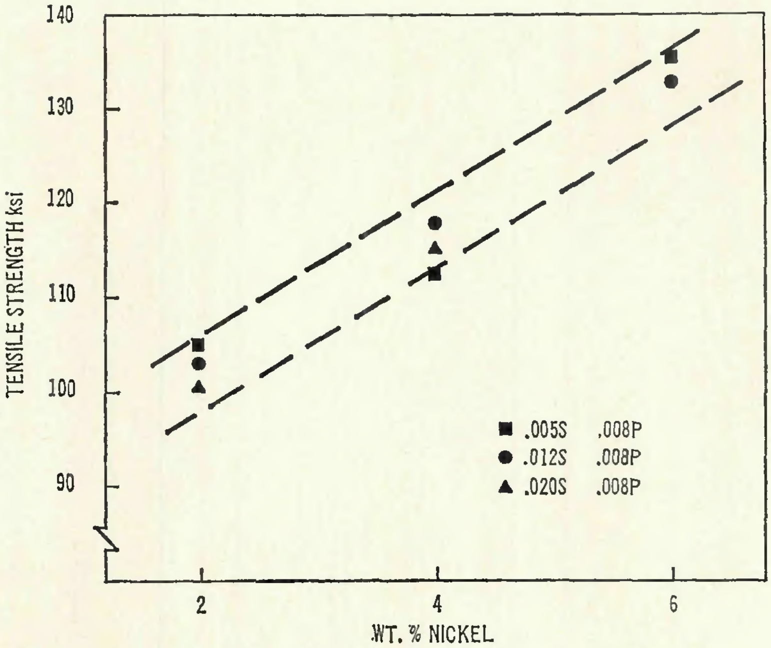


Fig. 5—Influence of nickel on weld tensile strength


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# Methods of High-Alloy Weldability Evaluation

**Proceedings of a Symposium Sponsored by the Welding Research Council and Published in November 1970**

The Workshop on Methods of Weldability Evaluation was organized and sponsored at the AWS Spring Meeting in Philadelphia, April 30, 1969, by the High Alloys Committee of the Welding Research Council. The purpose of the workshop was to exchange information on techniques and special apparatus used for measuring weldability of alloys. Emphasis was on methods, techniques and interpretation of data rather than on specific results. Although solicitation of several techniques was made, all but one of the submissions involved the Gleeble device and this one submission was withdrawn before the time of the session.

Initially no written submissions were requested; however, as a result of interest on the part of participants in the workshop, speakers were asked to prepare written papers for publication as a WRC monograph.

The papers included in the monograph are:

1. "Development of the R.P.I. Gleeble Equipment"—W. F. Savage (Abstract).
2. "Correlation of Hot Ductility Curves with Cracking During Welding"—W. Yeniscavich.
3. "Atmosphere Chamber for Test Specimens and Modification of the Dilatometer Control"—K. C. Wu.
4. "Evaluation of Creep During Rapid Heating"—D. Hauser and D. G. Howden.
5. "Multiple Thermal Cycles to Simulate Multipass Welding"—P. W. Holsberg and W. G. Schreitz.
6. "An Evaluation of the Ductility of Simulated Weld Fusion Zones in Inconel 718"—J. Gordine.
7. "Aerospace Application of the Gleeble"—W. P. Hughes.
8. "Dilatometric Measurements with the Aid of the R.P.I. 'Gleeble Machine' "—P. F. Martin and C. Rogues.

*Methods of High-Alloy Weldability Evaluation* is $3.00 a copy. Orders should be sent to the Welding Research Council, 345 East 47th Street, New York, N. Y. 10017.