Mechanical Properties and Microstructures of Inertia-Friction-Welded 416 Stainless Steel

A stainless steel normally considered nonweldable by fusion methods can be joined using friction welding

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ABSTRACT. Type 416, a resulfurized stainless steel, is normally not considered weldable; however, it can be welded using friction welding techniques. Tensile tests showed that with proper postweld heat treatment, friction-welded Type 416 samples can attain approximately 70% of the tensile strength of the base metal. Scanning electron microscope studies showed friction welding changes the orientation of the sulfide inclusions. Impact tests showed the sulfide inclusions made Type 416 very anisotropic and the reorientation of the inclusions by friction welding was responsible for changing the direction of maximum toughness. Friction welding can be used to fabricate parts from Type 416 if the design of the part accounts for the directional nature of the material and the weld.

Introduction

Inertia friction welding has been used for more than 30 years to solve the problem of joining difficult materials since little or no melting occurs along the weld interface. This process utilizes the frictional heat and pressure generated between a stationary and rotating workpiece to form a metallurgical bond. Several articles have addressed the process variables and other considerations in using this process (Refs. 1–7). Type 416 stainless steel is normally considered nonweldable by fusion methods, but it can be joined using inertia welding. This process and material may have significant advantages in some applications. For example, in the control valve market, there is a demand for low-cost globe valve plugs for use with mildly corrosive fluids — Fig. 1. A solution would be the production of valve plugs made from Type 416 stainless steel. These valve plugs are usually hardened to a Rockwell C range between 38 and 41, before machining, to eliminate warpage. Because the valve plug is manufactured from resulfurized steel (Type 416), it possesses a higher machinability rating than most martensitic stainless steels. The high sulfur can also contribute to the life of the plug and seat ring by resisting the onset of galling.

Plugs of 416 steel can be made of one solid bar or from two joined pieces. Mechanical joints can act as sites for crevice corrosion, reducing the life of the plug. Plugs made from solid bar are better, but the material wasted can be as high as 75–85%. The ideal way to make a plug is to weld a large-diameter bar for the head to a small-diameter bar for the stem, and then machine the plug from this stepped cylinder. Wallace (Ref. 5) reported Type 416 bar as weldable to Type 1020 steel plate in the production of vacuum covers. This achievement prompted studies of Type 416 friction welding by Valtek, Inc. (now Flowserve) and Brigham Young University (BYU). This study reports the mechanical properties and effects of sulfide inclusion and heat treatment for friction-welded Type 416 stainless steel.

KEY WORDS

Friction Welding
Inertia Friction Welding
Postweld Heat Treatment
Ductility
Impact Strength
Stainless Steels

Researchers at Valtek and BYU were encouraged by the advantages Pheasant (Ref. 8), Nicholas (Ref. 9), and Wallace (Ref. 5) listed in their reviews of the friction welding processes. Ellis (Ref. 10) added there is a direct increase in tensile strength with welding pressure until the weld reaches the base metal strength. Dunkerton's (Ref. 11) research found loss of toughness in the friction weld could be attributed to sulfide inclusions at the weld interface. Eberhard, Schaaf, and Wilson (Ref. 12) attributed this loss of toughness to the orientation of the sulfide inclusions in the weld. In a similar study, Lippold and Odegard (Ref. 13) investigated inertia friction welding of Type 303 S, noting a loss of tensile properties in that resulfurized, free-machining, austenitic stainless steel. Lienert, Nagy, and Baeslack (Ref. 7) investigated flow lines in inertia-welded 8009 aluminum. They showed the flow lines of Si-C-rich and Si-C-depleted bands followed spiral-shaped paths for inertia friction welds, which can account for changes in mechanical properties across the weld.

This paper investigates the friction welding of 416 stainless steel, its tensile strength and impact toughness. Welding parameters, sulfur orientation, and brittle failure, in relation to tensile and impact strength, are reported.

Experimental Method

Sample Manufacturing

Since the literature neither fully supported nor refuted the feasibility of friction welding 416 stainless steel, a set of experiments was undertaken to evaluate the merits of friction welding valve plugs. A total of 45 specimens were welded on a model 150 Caterpillar inertia welding machine with a piston area of 16 in.^{2}

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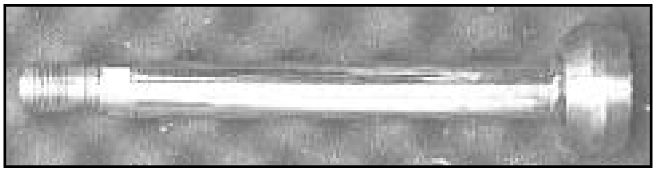

Fig. 1 — Globe valve plug.

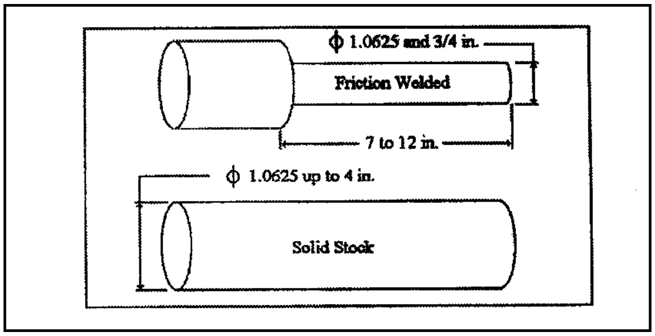

Fig. 2 — Solid stock vs. friction welding.

(103.2 cm^2). Welding tests were conducted using a 1$\frac{1}{16}$-in.-diameter (2.69-cm) bar to represent the plug head, and a ¾-in.-diameter (1.9-cm) bar to represent the plug stem. The annealed 416 stainless steel was obtained from Carpenter Steel, the nominal composition was carbon, 0.15%; manganese, 1.25%; phosphorous, 0.06%; sulfur, 0.15%; silicon, 1%; and chromium, 12–14% (Ref. 13). Prior to welding, the bar stock was austenitized at 1800°F (593°C) for 1 h, quenched in oil, then tempered at 700°F (371°C) for 1 h. The following machine ranges were used during the welding phase with the optimum settings indicated:

- weld speed range: 2300–3000 rpm (optimum 2500)
- upset speed range: 220–2000 rpm (optimum 2000)
- weld gauge pressure: 600 lb/in.^{2} (4.14 MPa)
- upset gauge pressure range: 800–700 lb/in.^{2} (5.52–4.83 MPa) (optimum 800)
- inertia: 16.5 slug ft^2 (219.4 N-m^2).

The bars were prepared for welding by cutting the 1$\frac{1}{16}$-in.-diameter (2.69-cm) bar into pieces 2–5 in. (5–13 cm) in length and the ¾-in.-diameter (1.9-cm) bar into pieces 7–12 in. (17–30 cm) in length. Figure 2 shows friction welding sample design as opposed to solid stock.

In an effort to find the best welding procedure for 416, samples were prepared using a combination of preheating, post-tempering, postaustenitizing, sanding, and cleaning to remove contaminates. Preheated samples were heated to 500°F (260°C) then welded. Various samples were subjected to one of the following post-tempering treatments:

- 1 h at 700°F (371°C)
- 2 h at 700°F (371°C)
- 7 h at 700°F (371°C)
- 1 h at 1100°F (593°C).

Samples were sanded smooth, cleaned with acetone, and air dried before welding. Cleaning tests were conducted to see if any contaminates affected the strength and ductility of the inertia weld. Postaustenitizing was done at 1800°F (982°C) for either 1 or 3 h. These tests were conducted to see if 416 inertia welds would be susceptible to hot or cold cracking, or heat-affected zone (HAZ) microfissures.

Hardness Tests

Hardness tests showed the variation in hardness occurred in a smaller space than could be measured with a standard Rockwell harness tester. Using a load-indenting microhardness tester, the hardness was more closely measured, taking measurement every 100–200 microns. These tests were conducted on a tensile specimen prior to testing in order to locate more precisely where the fractures were occurring. After breaking the tensile specimen, it was performed again to identify the site of the break and the hardness of the material at the break.

Tensile Tests

Thirty-six samples of welded Type 416 (see Fig. 4 and Table 2) were machined to a diameter of 0.75 in. (1.9 cm), then further machined to either 0.65 in. (1.65 cm) or 0.505 in. (1.28 cm) at the reduced section and tensile tested.

Impact Tests

Dunkerton (Ref. 11) indicated friction-welded parts could have low impact strengths, so impact studies were made using a standard Charpy impact tester at room temperature. Specimens of nonwelded 416 were tested with the sulfur inclusions parallel to the long axis of the impact specimen and transverse to the long axis of the impact specimen (both parallel and perpendicular to the notch). These results were compared with the impact values for welded 416 samples.

Bend Tests

Bend tests were also performed on welded and nonwelded 416 using a 1-in. (2.54-cm) bend radius.

Microscopy

A scanning electron microscope (SEM) was the easiest method for checking the orientation of sulfur inclusions. Samples were prepared using standard metallurgical methods. The welded bar stock was sectioned using a water-cooled, abrasive cutoff saw. These samples were then encased in standard 1-in. Bakelite mounts and polished. Samples were viewed with the normal SEM secondary electron (SE) and backscatter electron modes (BSE). X-ray mapping was also conducted on samples to find the relative location of iron, chrome, manganese, and sulfur.

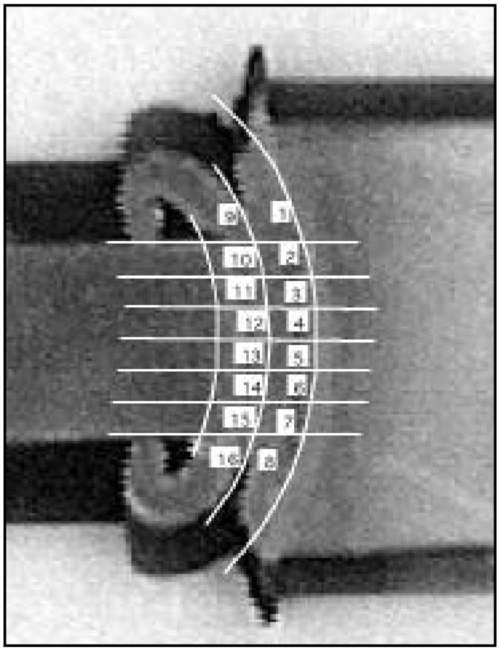

Fig. 3 — Rockwell test sample and grid.

Results and Discussion

Hardness Tests

To determine the hardness across the weld zone, samples were prepared by milling a flat surface through the middle of the weld. For testing, a second surface was milled parallel to the first, making each sample about ½ in. (1.27 cm) thick.

Table 1 — Rockwell C Hardness Tests

Sample Number Grid Location	1	2	3	4	5	Mean
1	47	48	48	48	49	48
2	47	48	48	48	49	48
3	44	49	48	49	49	47.8
4	46	48	43	47	48	46.4
5	45	49	45	47	49	47
6	47	49	47	48	50	48.2
7	40	48	49	48	49	46.8
8	38	47	49	49	48	46.2
9	42	45	34	46	43	42
10	46	38	34	47	37	40.4
11	44	36	36	44	39	39.8
12	42	45	34	46	43	42
13	38	38	38	47	35	39.2
14	48	46	35	48	37	42.8
15	38	49	35	46	37	41
16	49	45	30	45	39	41.6

Table 2 — Tensile Test Data Summary

Number of Tests	Diameter of Tensile Specimen in. (cm)	Average Failure Stress ksi (mPa)	Standard Deviations ksi (mPa)
12	0.505 (1.28)	160 (1116)	27 (186)
24	0.65 (1.65)	120 (827)	16 (112)

Table 3 — Tensile Results for 410 and Nonwelded 416

Material	Tensile Stress ksi (mPa)
Handbook value for 416 (Ref. 13)	190 (1310)
Machined sample of 416	185 (1275)
Handbook value for 410 (Ref. 13)	188 (1296)
Average for welded 410	206 (1420)

Figure 3 shows the back flat of one of these samples. Table 1 shows the results for five of the welded samples.

These results show the hardness of the weld is approximately the same across the weld. Tensile results show the strength is highest at the center of the weld and decreases toward the outside. These hardness results show this is not due to a variation in hardness across the welded sample. Microhardness tests made along a welded tensile specimen show values starting at 45 Rockwell C 6 microns left of the failure point, dropping to 33 Rc 3 microns left of the failure point, then rising to 47 Rc at the failure point. Readings were mirrored on the right side. The hardness was greatest where the failure occurred, showing hardness was not the major factor in welded specimen failure.

Tensile Tests

Thirty-six samples of welded Type 416 were machined to a diameter of 0.75 in. (1.9 cm.), then further machined to either 0.65 in. (1.65 cm) or 0.505 in. (1.28 cm) at the reduced section and tensile tested. Figure 4 shows the results of tensile tests for two samples superimposed on one graph. The stress is plotted as the vertical axis, and the strain is plotted as the horizontal axis. The upper plot is for a 0.505-in.-diameter welded sample of 410, and the lower plot is for a 0.505-in.-diameter welded sample of 416. The 416 is brittle, showing no plastic deformation, while the ductile nature of the 410 is obvious. Carpenter (Ref. 14) reports 416 austenitized at 1800°F (982°C), oil quenched, and tempered at 700°F (399°C) should have a ductility of 14% in a 2-in. specimen. It is obvious from Fig. 4 the welded 410 is ductile, but there is essentially no ductility for welded 416.

Table 2 shows the results of the tensile test data for the two diameters of machined and welded 416 tensile specimens. Figure 5 shows the data from Table 2 plotted graphically to show the effect of the diameter of the test specimen on the strength of the welded part. The data show the welded metal is strongest for the smaller diameter test specimen and, by inference, in the center portion. The strong diameter effect (shown in Fig. 5 and Table 2) is explained by the fact the orientation effect of inertia welding varies from the inside of the radius outward. Lienert, *et.al.* (Ref. 7), have shown there is a spiral-shaped displacement of material, with the displacement becoming increasingly tangential to the specimen as the distance from the center increases. With larger-diameter parts, the sulfur inclusions will tangentially reorient to a greater extent. It is expected the trend toward lower tensile strength would continue for even larger welded parts and tensile specimens if more than two diameters were tested.

Tests were made of inertia-friction-welded 410 stainless steel and machined, but not welded, 416 to check the welded sample results with handbook values of

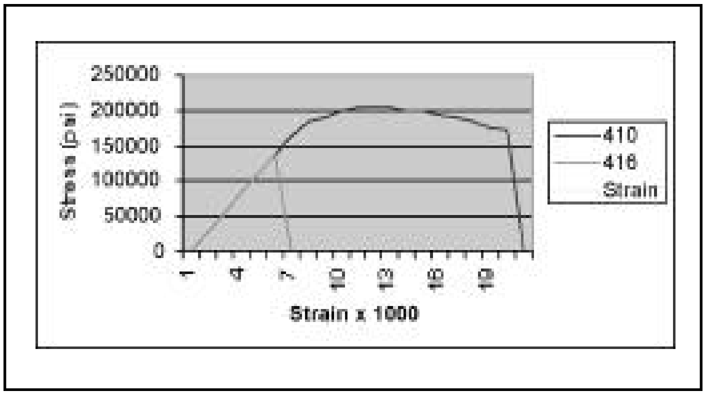

Fig. 4 — Plot of stress vs. strain for welded 410 (upper) and 416 (lower).

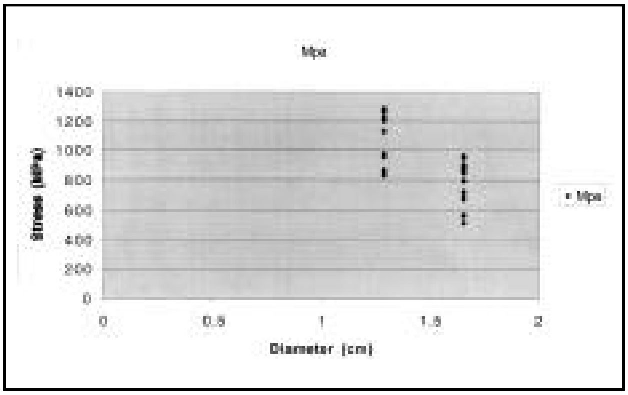

Fig. 5 — Strength vs. diameter for welded parts.

Table 4 — Effect of Heat Treatment

Material (dia. in.) (sample)	Treatment	Failure Stress ksi (mPa)	Brittle Failure
416 (0.65 in.) (7)	Postweld temper 1 h @ 700°F	127 (875)	Yes
416 (0.65 in.) (7)	Postweld temper 2 h @ 700°F	122 (841)	Yes
416 (0.65 in.) (2)	Postweld temper 7 h @ 700°F	127 (876)	Yes
416 (0.65 in.) (2)	Preheated and postweld temper @ 700°F	112 (774)	Yes
416 (0.505 in.) (2)	Cleaned postweld temper 1 h @700°F	133 (916	Yes
416 (0.505 in.) (2)	Postweld temper 1 h @ 1100°F	122 (854)	Yes
416 (0.505 in.) (3)	Postweld austenitized @ 1800°F no post temper	182 (1256)	Yes

Table 5 — Impact Tests

Sample	Charpy Impact Strength
Nonwelded, longitudinal	31 ft-lb (42 J)
Nonwelded, transverse	2 ft-lb (2.7 J)
Nonwelded, transverse, inclusions parallel to the notch	3 ft-lb (4.1 J)
Welded, austenitized, and tempered	1.5 ft-lb (2J)

these two stainless steels (Ref. 14). The 416 results shown in Table 3 were almost the same as the handbook value of 190 ksi (1310 MPa). The average of four results for 410 was a little above the handbook value, indicating the welding process was very satisfactory for 410 and, by extension, 416. The handbook values (Ref. 14) for 410 and 416 are for samples austenitized, oil-quenched, and tempered at 700°F (371°C) for 1 h. The samples were tempered at 700°F (371°C) because this would result in stress relief while keeping the material at the high strength level required for this application. The *Metals Handbook* (Ref. 15) shows 416 undergoes temper embrittlement for temperatures exceeding this value and suggests stress-relief annealing be performed in the range of 300–700°F (149–371°C). Carpenter (Ref. 14) also suggests avoiding the range of 750–1050°F (399–566°C) to avoid decreased impact strength and decreased corrosion resistance.

Table 4 shows the results of postwelding heat treatment tests made to see if the brittle nature (or lack of plastic deformation) of welded 416 could be overcome. Seventeen samples were tempered after welding to determine if brittle martensite was contributing to the brittle fracture. To test for cold cracking, three samples were also preheated to 500°F (260°C), then welded. Nine samples were postweld austenitized to see if this would remove the brittleness of the weld. Tempering temperatures from 700°F (371°C) to 1100°F (593°C) and reaustenitizing after welding at 1800°F (982°C) did not restore the ductility of the welded specimens.

Table 5 shows room temperature impact test results for samples machined from solid nonwelded bars with sulfide inclusions parallel to the long axis of the impact sample (nonwelded, longitudinal). The impact sample's long axis was machined perpendicular to both the inclusion's long axis and the notch on the impact specimen (nonwelded, transverse). The impact specimen's long axis also was perpendicular to the inclusion's axis, but the notch on the impact specimen was parallel with the inclusion's axis (nonwelded, transverse, parallel).

Basically, the long axis of the specimen (standard Charpy impact specimen) was cut from the rolling direction, which is also the inclusion's long axis direction in the material. The notch was cut from the top surface. The samples were also machined from the transverse direction, with the notch cut on the top. That puts the notch parallel with the inclusions and the specimen perpendicular to the inclusions. When the sample is cut from the transverse direction and the notch cut on the side of the machined impact specimen, the inclusions are perpendicular to both the sample and the notch.

A sample was also re-austenitized at 1800°F (982°C) then tempered for 1 h at 700°F (371°C), which did not improve the impact properties (austenitized and tempered). The impact results show the highest value of impact strength is for the sulfur inclusions located parallel to the axis of the impact specimen. When sul-

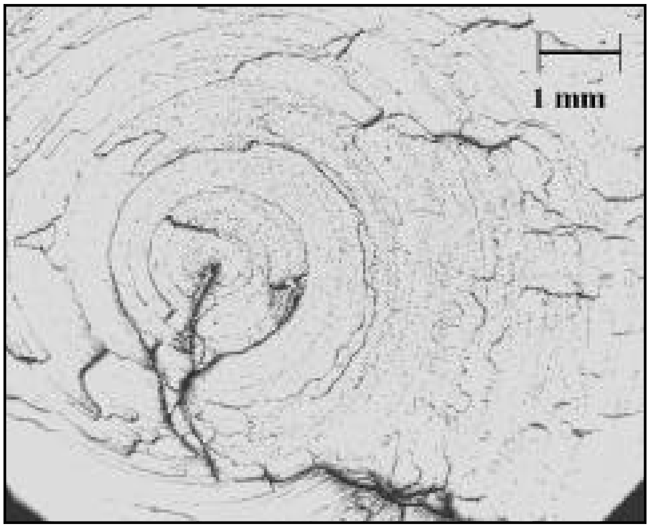

Fig. 6 — SEM photo of the circular fracture pattern (10X).

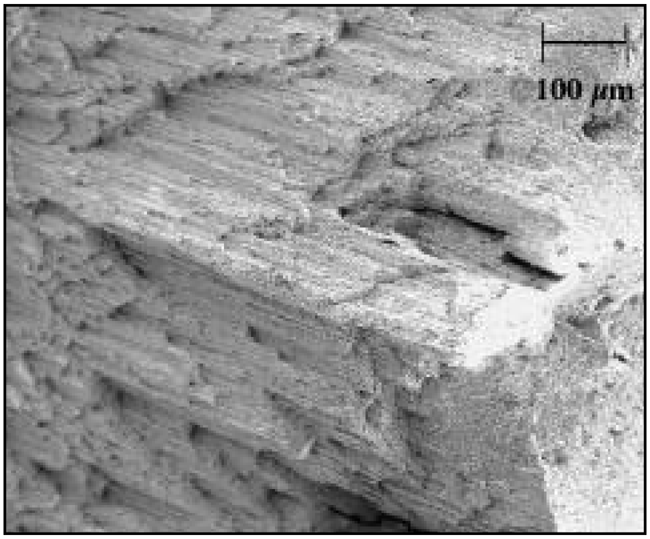

Fig. 7 — Fracture pattern for a nonwelded impact specimen (100X).

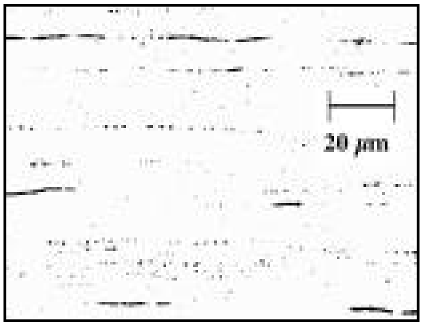

Fig. 8 — SEM (BSE) sulfide inclusions axially aligned with the plug stem (500X).

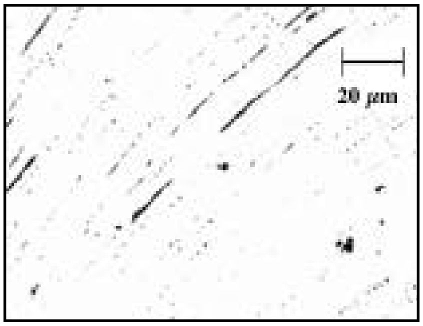

Fig. 9 — Sulfide inclusions beginning to align with the weld in the HAZ (500X).

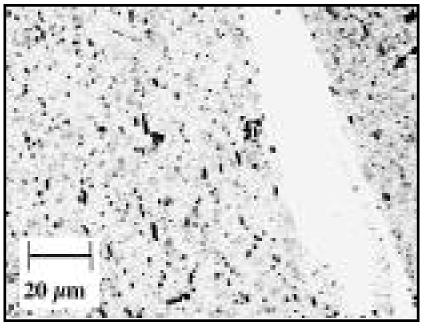

Fig. 10 — Sulfide inclusions in the weld area (500X).

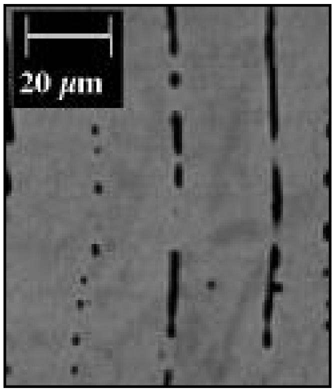

Fig. 11 — SEM (BSE) image of inclusions (500X).

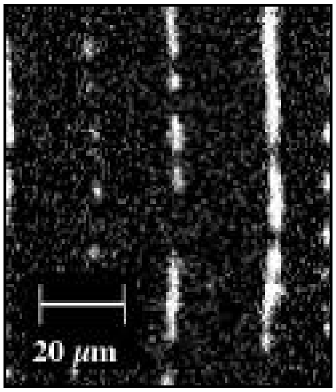

Fig. 12 — Location of S (500X).

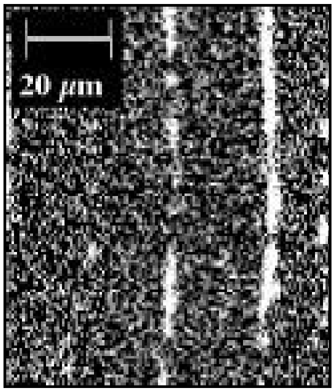

Fig. 13 — Location of Mn (500X).

fur inclusions are located in a direction transverse to the impact specimen, the value is markedly lowered. It is slightly higher (3 ft-lb) when the inclusions are located parallel to the notch on the impact bar rather than perpendicular to them (but still transverse to the axis of the specimen). The value of impact strength for the welded sample is about the same value as that for the nonwelded, with the exception of the much higher value (31 ft-lb) for the specimen with the longitudinally located inclusions. The sulfide inclusions decrease the impact strength of the samples by a factor of approximately 15. This is certainly related to the decrease in elongation for unwelded 416 from 14% (Ref. 14) to almost nothing. These results corroborate those of Dunkerton (Ref. 11), showing the loss of impact strength is due to the orientation of sulfur inclusions in the weld area. Lienert (Ref. 7) has shown how inclusions reorient during the welding process.

Bend Tests

A nonwelded sample failed between 10 and 12 deg, and the average for three welded samples was between 5 and 7 deg using a bend radius of 1 in. (2.54 cm). In this test, welding also decreased the ductility of the sample.

Microscopy

Figure 6 shows a scanning electron microscope (SEM) secondary electron (SE) image of the circular fracture from a welded impact sample. This pattern was the same as the fracture pattern of the tensile specimens. Compare this with the close-up of the fracture surface of a nonwelded parallel impact specimen (Fig. 7). The welded sample (Fig. 6) has small corners that lifted and separated like an orange peel, while the nonwelded sample has the tough fibrous appearance of wood. The mode of failure is obvious here; the sulfide inclusions provide "stress risers," or notches, that permit fracture with no elongation and with a much decreased impact strength. The situation in the welded material is similar to the effect caused by graphite flakes in gray cast iron. Since the sulfide is in stringers, the effect is not noticeable in the longitudinal direction.

Figure 8 shows a BSE image of the inclusion found in Type 416. The inclusions have elongated along the axis of rolling. Figure 9 shows these inclusions begin to change directions in the HAZ.

In Fig. 10, the inclusions at the center of the weld are shown. A piece of nickel weld rod was placed in the center of one of the pieces before welding to make it easy to find the weld interface and can be seen as the bright area in the figure.

Figure 11 shows a SEM backscatter (BSE) image of the inclusions.

Figures 12 and 13 show the X-ray mapping of certain elements in a 416 sample at a magnification of 500X. White shows the areas where the respective element is found, and black shows a lack of that element. By comparing Fig. 10 and Fig. 11, it can be seen most of the sulfur is in the inclusions, as expected. Figure 13 shows most of the manganese is in the inclusions; however, a substantial amount is still in the matrix. These maps show the inclusions are sulfide inclusions, as expected, with manganese also associating with the inclusion.

X-ray mapping studies were done on all other elements in the sample. Results indicate sulfur and manganese are the major constituents in the inclusions, with no appreciable quantity of chrome or other elements associated with the inclusions.

Conclusions

This study investigated welding 416 for a control valve application requiring the material be heat treated before machining. The samples were welded using friction inertia welding with satisfactory results for tensile strength considerations.

More than 84% of the handbook values were achieved for 0.505-in.-diameter (1.28-cm) samples, but only 63% for 0.65-in. (1.65-cm) samples.

Sulfide inclusions incorporated in this highly resulfurized steel were reoriented by the friction-welding process. The particles became more oriented as the diameter of the part increased. This caused a decrease in strength as the diameter of the welded part increased. The reorientation of the sulfide particles caused the ductility of the welded part to become essentially zero in the axial direction and the impact strength to decrease by approximately a factor of 15.

The brittle nature of the welded part was investigated using tensile tests, impact tests, and SEM photographs. Several heat treatments were investigated in an attempt to restore the ductility of the samples. No heat treatment could be found that restored the ductility and impact strength. The 416 can be friction welded with adequate tensile strength, but there was a severe loss of ductility and impact strength due to the reorientation of the sulfide inclusions.

Acknowledgment

Valtek, Inc. (now Flowserve), of Springville, Utah, funded this research.

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◆ Why was the work done?
◆ What was done?
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With those questions in mind, most authors can logically organize their material along the following lines, using suitable headings and subheadings to divide the paper.

1) **Abstract.** A concise summary of the major elements of the presentation, not exceeding 200 words, to help the reader decide if the information is for him or her.

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3) **Experimental Procedure, Materials, Equipment.**

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5) **Conclusion.** An evaluation and interpretation of your results. Most often, this is what the readers remember.

6) **Acknowledgment, References, and Appendix.**

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