N72- 24536

N72- 24536

NASA TM X-68070

NASA TECHNICAL MEMORANDUM

NASA TM X-68070

STATE-OF-TECHNOLOGY FOR JOINING TD-NiCr SHEET

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TECHNICAL PAPER proposed for presentation at
Second International Symposium on Superalloys sponsored
by the American Institute of Metallurgical Engineers
Seven Springs, Pennsylvania, September 18-20, 1972

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E-6954

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Summary

At the current state-of-technology there are many joining processes that can be used to make sound welds in TD-NiCr sheet. Some of these that are described in this report are electron beam welding (EBW), gas-tungsten arc welding (GTAW), diffusion welding (DFW), resistance spot welding (RSW), resistance seam welding (RSEW), and brazing. Roll welding (RW) and expolsion welding (EXW) have not been developed to the point where they can be used to make sound welds in TD-NiCr. The strengths of the welds made by the various processes show considerable variation, especially at elevated temperatures. Most of the fusion welding processes tend to give weak welds at elevated temperatures (with the exception of fusion-type resistance spotwelds). However, solid-state welds have been made with parent metal properties. The process used for a specific application will be dictated by the specific joint requirements. For example, if a particular joint will never be highly stressed at elevated temperatures, fusion welding processes may be satisfactory. In highly stressed joints at elevated temperatures, one of the solid-state processes, such as DFW, RSW (solid-state or fusion), and RSEW, offer the most promise.

Joining work that has previously been done on TD-NiCr by various organizations, both privately supported and under Air Force and NASA contracts, is described in this summary. Current work is also described that is being done at General Dynamics/ Convair (under NASA contract) and at NASA/Lewis to develop and evaluate DFW, RSW, RSEW, and brazing. Preliminary comparisons of joining processes are made for typical applications.

A brief description of the manufacture of TD-NiCr sheet by a recently standardized process (under NASA contract) also is given.

Introduction

The dispersion strengthened alloy TD-NiCr (Ni-20Cr-2ThO_2) is being considered for use in various high temperature applications requiring high creep strength and good oxidation resistance. NASA is currently interested in this material for possible use in re-entry protection heat shields for future space shuttle vehicles and in high temperature components of jet engines (ref. 1). In these applications, TD-NiCr would be used mostly in the temperature range of about 980° to 1200° C (1800 to 2200° F). This material appears promising for use in this range because it has better creep strength than conventional superalloys and good oxidation resistance.

The purpose of this report is to summarize the current state-of-technology for joining TD-NiCr sheet. Some attempts have been made to apply fusion welding processes to this material. But fusion welding processes melt the material and destroy its uniformly-fine ThO_2 dispersion and highly-textured microstructure which are responsible for its good elevated temperature strength. For this reason, most effort has been directed toward use of solid-state welding processes and brazing for joining TD-NiCr. But widely-different results have been attained. This report summarizes results of investigations with welding processes such as gas-tungsten arc, electron beam, diffusion welding, resistance spot welding, resistance seam welding, brazing, roll welding, and explosion welding. Resulting strength properties are given where available.

In preparing this review, we have attempted to include the most significant results from all of the pertinent literature references found. In addition, we have included more recent (previously unreported) results from current NASA-sponsored programs that are directed toward this subject (refs. 2, 3, and 4). The results and properties included in this summary were obtained from work conducted by various organizations funded privately or under Air Force and NASA contracts, and from NASA-Lewis Research Center in-house technology programs. (We want to express appreciation to the various individuals and organizations that have allowed us to include their data in this summary.)

Manufacture of TD-NiCr Sheet

TD-NiCr has been in an advanced development stage in which the sheet manufacturing process and resulting properties have varied considerably. Only recently has the sheet manufacturing process been standardized to provide consistently uniform and reproducible properties (ref. 5). As a result, most joining studies reported to date have exhibited scattered strength properties which may, in part, be due to variations in sheet properties. Therefore, joint properties reported in this summary may not be fully characteristic of the optimum weld properties that can be obtained with this material. Work is currently underway (in-house at NASA-Lewis and at General Dynamics/Convair under a NASA contract) to more completely characterize the properties of various types of weldments in TD-NiCr sheet produced by the recently standardized process.

TD-NiCr is produced by Fansteel, Inc. in several different sheet forms. The material is available in foil, sheet, and plate gages. The mechanical and metallurgical properties of the commercial-grade sheet gages (0.25 mm (0.010 in.) to 1.5 mm (0.060 in.) thick) are roughly the same. But commercial-grade foil (0.075 mm (0.003) thick) and plate (>3.2 mm (0.125 in.) thick) have lower mechanical properties and different metallurgical properties (e.g., grain size) than sheet. However, these variations in mechanical and metallurgical properties have little influence on the weldability of the different forms of commercial-grade sheet.

The basic manufacturing process has recently been standardized by Fansteel in a program conducted under a NASA contract (ref. 5). The resultant process is outlined in flow-diagram form in figure 1. The sheet manufacture begins with a unique powder production process which results in a uniform dispersion of fine ThO_2 dispersoid in a Ni-Cr matrix. This powder is then isostatically compacted at room temperature and sintered at approximately 980° C (1800° F) in dry hydrogen for about 2 hr. The powder metallurgy billet is further densified by roll consolidation at 1090° C (2000° F). Rolling to final gage is done at 760° C (1400° F).

To obtain TD-NiCr in the fine-grained, unrecrystallized condition, the sheet is belt sanded at this point and given no further processing. This type of sheet will be termed "specially-processed" in this report.

To obtain the more typical "commercial-grade" TD-NiCr sheet, the product is given a recrystallization anneal at 1180° C (2150° F) for 2 hr in dry hydrogen. In this recrystallized condition, the TD-NiCr grain size is quite large to help provide good high temperature strength. For heavier sheet gages (0.25 to 1.9 mm (0.020 to 0.075 in.), the recrystallized sheet is then surface sanded with a nominal 120-grit belt. For thinner gages (0.25 to 0.50 mm (0.010 to 0.020 in.), the recrystallized sheet is surface sanded, given a light cold-roll pass (~2 percent reduction) for flatness, and annealed at 1180° C (2150° F). To obtain foil, the 0.25 millimeter (0.010 in.) recrystallized sheet is cold rolled to the desired gage and given a second recrystallization anneal at 1180° C (2150° F). Surface cleaning and inspection are the final steps. TD-NiCr foil has a smaller grain size than sheet as a result of the additional cold rolling and recrystallization steps.

Results of Fusion Welding Studies

In fusion welding TD-NiCr, melting of the TD-NiCr takes place whether filler material is used or not. As an example of fusion welding, the microstructure of a typical electron beam (EB) weld in 0.25 millimeter (0.010 in.) thick commercial-grade TD-NiCr is shown in figure 2 (ref. 6). The dendritic solidification pattern and general darkening of the microstructure mark the fusion zone of the weldment (i.e., zone of melted material). The dark areas in the fusion zone are probably regions of thoria that have segregated and agglomerated during melting and solidification. It is also evident from figure 2 that the TD-NiCr microstructure has been greatly altered in the fusion zone. All benefits of thermomechanical processing and texture in the TD-NiCr have been lost in the fusion zone. In fact, the fine grain size, dendritic microstructure in the fusion zone would be expected to be weak at elevated temperatures. Essentially, fusion weldments should have the strength of Ni-20Cr. Joint efficiencies of 30 to 50 percent in tensile testing at elevated temperatures result (refs. 7, 8 and 9). And it is expected that the creep-rupture strengths of fusion welds would be even lower (although these types of tests have not been reported for fusion welded TD-NiCr).

Fusion welding TD-NiCr is of interest, however, for making joints in regions of low stress. The fusion welding processes have the advantages over solid-state welding and brazing of being more easily applied and inspected after welding.

Johnson and Killpatrick (ref. 9) reported a preference for electron beam welding (EBW) over gas-tungsten arc welding (GTAW) for joining 0.25 millimeter (0.010 in.) thick commercial-grade TD-NiCr. With GTAW, a wider fusion zone and more ThO_2 agglomeration in the heat-affected-zone (HAZ) occurred than in EBW. Failure occurred in the HAZ, and good flow was not obtained in the fusion zone of GTA welds. In contrast, EBW resulted in narrow fusion and HAZ zones, good flow, and good weld-bead shape, although thoria agglomeration naturally occurred in the fusion zone. Both simple butt and burn-down flange configurations were evaluated on 0.25 mm (0.010 in.) thick sheet, as indicated in table 1. Simple butt joints were more fully evaluated by elevated temperature tensile testing than burn-down flange joints since the thinner weld zones achieved in simple butt joints were more desirable. The 1090° C (2000° F) tensile strength of 34 MN/m^2 (5 ksi) shown in table 1 represents about 30 percent joint efficiency.

In another study, Rupert (ref. 10) GTA-welded both 0.5 millimeter (0.018 in.) and 1.6 millimeter (0.060 in.) thick commercial-grade TD-NiCr with Hastelloy X and Inconel 62 filler materials. Melting of the TD-NiCr was minimized to avoid the problem previously described. The Hastelloy X filler was preferred over the Inconel 62 because the lower melting point of Hastelloy X allowed a lower heat input and, thus, less melting and a narrower HAZ in the TD-NiCr. Also, as seen in table 1, the welds made with Hastelloy X were stronger in room temperature tensile tests than those made with Inconel 62. However, the elevated temperature strengths of these weldments cannot be expected to be any higher than the filler material strengths.

Both GTAW and EBW have merits and disadvantages. EB welds can be quite strong and can have a narrow HAZ (with minimal metallurgical damage to parent material), but this requires very good fitup, usually a vacuum chamber, remote access to the joint, and pumpdown time. GTAW does not require a vacuum chamber but results in a wide HAZ and the use of groove preparation and filler material in some cases. But, both processes can easily give sound welds in TD-NiCr. The relative merits of each process would have to be compared for each particular application before a final selection could be made.

Results of Solid-State Welding Studies

Diffusion Welding

Several organizations have made diffusion welds in TD-NiCr sheet (e.g.-refs. 2, 4, 8, 9, and 11). Table 2 shows some of the diffusion welding parameters used and the sheet thicknesses welded. For welding commercial-grade TD-NiCr sheet, temperatures in excess of 1150° C (2100° F) have generally been used with various combinations of pressure and time. However, regardless of the welding parameters used, diffusion welds in commercial-grade TD-NiCr sheet have been plagued with the formation of small, recrystallized grains at the weld interface, as shown in figure 3(a). The small grains are weak at elevated temperatures and cause low weld strengths (0 to 60 percent joint efficiency in creep-rupture shear tests - ref. 8). The small grains form from recrystallization of locally-strained material around the weld interface. This local straining results from cold working during belt sanding of the surfaces prior to welding. Also, deformation of surface asperities during welding causes highly localized plastic strain of material already cold worked. Heating then results in recrystallization at the weld interface.

We have previously shown (ref. 8) that small grains at the weld interface can be eliminated by flattening surface asperities and removing the cold worked surface material by electropolishing or chemical polishing prior to welding, as shown in figure 3(b). However, the commercial-grade TD-NiCr microstructure is very stable at the welding temperatures, and significant grain growth across the weld interface does not occur. The result is a fairly-continuous weld line which is essentially a grain boundary. At elevated temperatures, this type of weld is strong, but fracture occurs at the weld line which is an undesirable condition.

We have also shown in reference 8 that the continuous weld line can be eliminated by diffusion welding TD-NiCr in the specially-processed (SP) condition. The SP material is obtained before the final recrystallization heat treatment, as shown in figure 1. As with the commercial-grade material, it is necessary to electropolish or chemically polish the surfaces of the SP material prior to welding. Diffusion welding can be accomplished at a temperature below the recrystallization temperature (circa 870° C (1600° F). The microstructure is then recrystallized after welding by heating to a temperature above the recrystallization temperature. As seen in table 2, 1.6 millimeter (0.060 in.) thick SP TD-NiCr was diffusion welded with a two-step welding cycle. The first step (705° C (1300° F)/210 MN/m^2 (30 ksi)/1 hr) provided intimate contact and welding, while the second step (1190° C (2175° F)/15 MN/m^2 (2 ksi)/2 hr) recrystallized the microstructure and provided grain growth across the weld line. This welding procedure completely eliminated the weld line, as shown in figure 3(c). Creep rupture shear strength of diffusion welds made in the SP material equalled the parent metal strength, as shown in figure 4. Fracture took place through the parent material, away from the weld line. Welds made in commercial-grade TD-NiCr also equalled the parent metal strength, as shown in figure 4, but fracture took place at the weld line. Average tensile-shear strengths at 1090° C (2000° F) for welds in the SP and commercial-grade 1.6 millimeter (0.060 in.) thick TD-NiCr are shown in table 2.

More recently (unpublished work), we have extended the work of reference 8 to shorten the welding time required. The two-step welding cycle used for 1.6 mm (0.060 in.) thick SP TD-NiCr has been shortened to one step and used to weld 0.4 millimeter (0.015 in.) thick SP TD-NiCr, as also shown in table 2. Specimens were welded at 760° C (1400° F)/210 MN/m (30 ksi)/1 hr since the ductility of SP TD-NiCr is higher at 760° C than at 705° C (13 to 27 percent vs. 10 to 20 percent elongation), as recently determined by Convair personnel (ref. 3). The welds were recrystallized at 1180° C (2150° F) in a hydrogen furnace after welding. It was found that a surface preparation of 320-grit sanding plus chemical polishing prior to welding was adequate in avoiding the formation of small grains at the weld interface. Specimens were welded and notched, tensile-shear specimens with a 2t overlap were prepared, as shown in figure 5. Microstructures of a typical weld are shown in figure 6 after the recrystallization heat treatment and also after notching and creep-rupture testing. It is evident that the weld line was eliminated by recrystallization and grain growth. Creep-rupture shear testing resulted in parent metal tensile and bending failure, as shown in figure 6(c). It can be seen that the weld was highly stressed as shown by the porosity and grain boundary separation that occurred in the overlap region. Creep-rupture data for other welds made with the same parameters are shown in figure 7. For comparison, the average strength of 1.6 millimeter (0.060 in.) thick parent metal and weldments from figure 4 are shown as a line on this plot. The 0.4 millimeter (0.015 in.) thick TD-NiCr welds are expected to have similar strengths, since failure occurred in the parent material away from the weld for all points shown in figure 7. Unfortunately, parent metal failure occurred before the specimens lasted long enough to fall on the line.

Although this welding method has resulted in successful welds, occasional difficulties have been encountered due to localized regions of high deformation during welding. For example, figure 8 shows the effect of excessive localized deformation (circa 1 percent decrease in thickness) on the microstructure of an SP weld after a recrystallization heat treatment. The small, dark grains located on a 45° shear plane are very similar to the unrecrystallized grain size. But they apparently have undergone recrystallization since they are stable and resisted grain growth to the commercial-grade TD-NiCr grain size. Temperatures as high as 1260° C (2300° F) could not cause the small grains to grow any larger. The small grains are very weak at elevated temperatures and caused premature failure in creep-rupture shear testing. Failure at the small grains is shown from the opposite side in figure 8(c)

Work is now being done to determine if the pressure necessary for diffusion welding unrecrystallized TD-NiCr at 760° C (1400° F) can be reduced to provide a safety margin for avoding the local deformations that produce these stable small grains. Work is also being done on commercial-grade TD-NiCr to see if the 760° C (1400° F) welding cycle can be used.

The easiest way to determine the quality of solid-state welds in TD-NiCr is by metallurgical inspection of the weld line. The poorest welds are seen to have small, recrystallized grains at the weld line. A better condition is the presence of a continuous weld line, similar in appearance to a grain boundary. And the best welds show the complete elimination of the weld line and the commercial-grade TD-NiCr microstructure throughout. The best welds are achieved by chemical or electrochemical surface preparation and the use of SP TD-NiCr. It is felt, then, that optimum solid-state welds can be produced by the technique previously described and parent metal properties can be attained at all temperatures. Further testing of diffusion welds is required to prove this.

Resistance Spot Welding

As seen in table 4 and the appendix, extensive work has been done in resistance spot welding (RSW) TD-NiCr sheet by various organizations (refs. 2, 9, 12, 13 and 14). In fact, more work has been done with the RSW process than with any of the other welding processes. Accordingly, this summary section will be more extensive. Thicknesses ranging from 0.25 to 1.5 millimeters (0.010 to 0.060 in.) have been spotwelded with both single and three-phase equipment. TD-NiCr foil (0.08 mm (0.003 in.) has also been spotwelded by Johnson and Killpatrick (ref. 9) although their spot parameters are not included in the appendix. Both fusion and solid-state spotwelds have been made, and both commercial-grade and specially processed (SP) TD-NiCr have been spotwelded. Sound, defect-free spotwelds have been made for the thickness shown in table 4 with each of the combinations of parameters listed in the appendix. In general, strengths of both fusion and solid-state spotwelds in TD-NiCr have been surprisingly high as will be illustrated.

Microstures of fusion spotwelds. - A cross-section of typical fusion spotweld in commercial-grade TD-NiCr is shown in figure 9. This particular spotweld was made recently in the work of reference 3, but it is representative of most of the fusion spotweld microstructures that result from parameters shown in the appendix (see refs. 9 and 13). By using a shorter welding time (one cycle of single-phase power as compared to two or more cycles of three-phase power) we obtained (ref. 2) a somewhat different microstructure, as shown in figure 10. This spotweld does not appear to have been as extensively melted as the spotweld shown in figure 9. Less melting may be desirable if the amount of thoria segregation and agglomeration can be decreased from that occuring in more extensively-melted spotwelds. However, the actual thoria distribution has yet to be determined in both of these cases. Even if the original thoria dispersion could be retained, the loss of the original TD-NiCr texture, (which was probably lost in both cases) may still be the overriding factor in loss of elevated temperature strength in these types of welds, particularly creep-rupture strength.

Microstructures of solid-state spotwelds. - Solid-state spotwelding commercial-grade TD-NiCr has been done with various welding parameters, as shown in the appendix. Most solid-state spotwelding has been plagued with the formation of small, recrystallized grains at the weld interface, just as described under "Diffusion Welding" and shown in figure 3(a). Again, the small grains can be eliminated by removing the asperities and cold-worked surface layer (resulting from surface sanding) by chemical polishing. A typical solid-state spotweld made with chemically-polished surface prepartion is shown in figure 11 (ref. 2). The continuous weld line that is present is essentially a grain boundary which could not be eliminated by further heat treatment. It has been reported by two organizations (refs. 12 and 13), however, that the strength of these types of welds can be improved by postheating.

Specially-processed TD-NiCr sheet has been successfully solid-state spotwelded (ref. 2) with the parameters shown in the appendix (see footnote). A typical cross-section through a spotweld is shown in figure 12. In the as-welded condition, the microstructure is only slightly darkened in the vicinity of the weld line (figs. 12 (a), (b), and (c)). But, close observation of figure 12(c) reveals the presence of two small white grains which indicates the beginning of recrystallization. This means that the material in the vicinity of the weld line was heated to about (870° C) 1600 F, the lowest temperature at which recrystallization will occur in this material. A subsequent 2-hour recrystallization anneal of the entire spotweld at 1200° C (2200° F) completely eliminated the weld line by recrystallization and grain growth, as shown in figures 12(d) and 12(e). This is an optimum solid-state weld as judged by light microscopy since the weld line is undectable.

Tensile-shear strength. - The effect of material thickness on spotweld shear strength is shown in figure 13. At room temperature, the shear strengths of both solid-state and fusion spotwelds depend roughly on material thickness since "button pull-out" failures commonly occurred at the edge of the spotweld and through the parent material. Spotweld shear strengths varied from 140 MN/m^2 (20.4 ksi) to 342 MN/m^2 (49.7 ksi) for 0.25 to 1.5 millimeter (0.010 to 0.060 in.) thick TD-NiCr. At 1090° C (2000° F) and 1200° C (2200° F), variation in tensile shear strength is not dependent on material thickness as was the case at room temperature. At 1090° C (2000° F), the spotweld shear strength ranges from 14 MN/m^2 (2.0 ksi) to 43 MN/m^2 (6.2 ksi); and at 1200° C (2200° F), it ranges from 25 MN/m^2 (3.6 ksi) to 41 MN/m^2 (6.0 ksi) regardless of material thickness. Both "button-pullout" and failures through the weld occurred regardless of strength. (Additional tensile-shear strength values of TD-NiCr spotwelds are tabulated in the appendix.)

It should be pointed out that in figure 13 fusion spotwelds appear to be stronger than solid-state spotwelds. However, the solid-state spotwelds shown in figure 13 were all not made under optimum conditions, and most contain small grains at the weld interface, as previously described. Therefore, the real potential of solid-state spotwelding is not shown in figure 13, and the data are only meant to be representative of the current state-of-technology. Variations in sheet quality before recent standardization of the manufacture of TD-NiCr sheet may also be responsible for some of the scatter in figure 13.

Creep-rupture shear strength. - Creep-rupture shear testing of fusion and solid-state spotwelds in commercial TD-NiCr has been conducted by several organizations (refs. 2, 9, and 13). Representative creep-rupture shear loads and shear stresses as functions of time to rupture are shown in figure 14 (ref. 2). Failure shear load is included for comparison to rivets and "load per spot" data for other materials. The reversal of relationship between the fusion and solid-state plots for "shear load" and "shear stress" apparent in figure 14 results from the solid-state spotwelds having a larger diameter and correspondingly larger area than the fusion spotwelds. Also, the 100-hour creep-rupture shear strengths from references 2, 9, and 13 are summarized in table 5. The failure-mode in these tests was generally through the spotweld.

Yount, et.al. (ref. 13) and Carpenter (ref. 12) preferred solid-state over fusion spotwelds. Yount conducted creep-rupture tests only on solid-state spotwelds in 0.6 millimeter (0.025 in.) and 1.0 millimeter (0.040 in.) thick TD-NiCr as seen in table 5. Spotwelds in 0.6 millimeter (0.025 in.) TD-NiCr were stronger than spotwelds in 1.0 millimeter (0.040 in.) TD-NiCr (23 MN/m^2 (3.3 ksi) as compared to 16 MN/m^2 (2.3 ksi) 100-hour creep-rupture life). However, there was scatter in these data (ref. 13) as some specimens failed on loading at stresses similar to the 100-hour creep-rupture shear stress for both fusion and solid-state spotwelds.

In contrast, Johnson and Killpatrick (ref. 9) preferred fusion over solid-state spotwelds because their results indicated higher creep-rupture shear strengths in fusion welded samples, as shown in table 5. Again, for both fusion and solid-state spotwelds, some specimens failed on loading at stresses similar to the 100-hour creep-rupture shear strengths. One hundred-hour creep-rupture shear strengths at 1090° C (2000° F) of 31 MN/m^2 (4.5 ksi) for fusion spotwelds and 17 MN/m^2 (2.5 ksi) for solid-state spotwelds in 0.4 millimeter (0.020 in.) TD-NiCr were indicated.

In further contrast, our recent results (ref. 2) indicate that fusion and solid-state spotwelds in 0.4 mm (0.015 in.) thick commercial-grade TD-NiCr had similar creep-rupture shear strengths, as shown in figure 14 and table 5. Note however, that the larger-area solid-state weld could support more load. At 1090° C (2000° F) for 100-

hour creep-rupture shear tests, shear strengths of 27 MN/m^2 (3.9 ksi) and 23 MN/m^2 (3.4 ksi) resulted for fusion and solid-state spotwelds, respectively.

Creep-rupture shear strengths of fusion spotwelds have been surprisingly good in several investigations. The reason for this is not completely understood at this time. Melting of the TD-NiCr in the spotweld nugget disrupts the thoria dispersion to some degree (as demonstrated in ref. 9) and changes the TD-NiCr texture. This should have an adverse effect on elevated temperature strength, especially creep-rupture strength. One possible explanation is that the unmelted TD-NiCr material surrounding the spotweld nugget somehow provides a strengthening effect. Perhaps the creep resistance of the unmelted TD-NiCr prevents deformation and delays failure of the spotweld nugget.

Room temperature fatigue strength. - Fatigue testing of spotwelds in 0.5 millimeter (0.020 in.) TD-NiCr were also conducted by Johnson and Killpatrick (ref. 9). Fusion and solid-state spotwelds made with the schedules shown in the appendix were tested, and the results are shown in figure 15. As can be seen, the fatigue strengths of both the fusion and solid-state spotwelds are very similar, especially at lower loads. Approximately 4.45 N (100 lbs) maximum load at an R value of 0.2 can be supported with either type of spotweld for one million cycles.

Preliminary fatigue tests at NASA-Lewis (ref. 2) on fusion and solid-state spotwelds in 0.4 millimeter (0.015 in.) thick TD-NiCr are shown in figure 16. The parameters used to make these welds are shown in the appendix. In this case, the solid-state spotwelds are slightly stronger than the fusion welds, probably due to a larger spot diameter (5.5 mm (0.22 in.) vs 4.3 mm (0.17 in.). It appears that both tyes of spotwelding will support over 445 N (100 lbs) maximum load at an R value of 0.2 for one million cycles.

However, these fatigue failure loads are low when compared to room temperature tensile failure loads shown in the appendix (445 N; 100 lbs vs. approximately 3,000 to 4,000 N; 700 to 900 lbs). This degradation of spotweld strength with fatigue exposure could limit the use of spotwelds where high room temperature fatigue strength is required. It should be kept in mind that the fatigue data in this summary are only for single spots. Multiple spots, as would be used in a structure, should be tested before spotwelding is ruled out for a particular application.

General. - The wide data scatter observed in many of the property tests (for example, some creep-rupture specimens failed on loading while others at similar stress-levels lasted over a hundred hours) is probably due to variations in spotweld strength. These variations may not be great but are amplified by the relatively flat creep-rupture curves for TD-NiCr. Great differences in time-to-rupture may be due to small differences in strength differentiating between failure on loading and 100-hour life because of the flat creep-rupture curves.

However, variation in spotweld strength has always been one of the major drawbacks to the use of spotwelds in critical applications. These variations arise from differences in material thicknesses, sheet flatness, surface finish, surface cleanliness, etc. (i.e., anything that can affect the electrical resistance of the materials to be spotwelded). It is felt that more in-process control and inspection, as well as postweld NDE should be used to increase spotweld reproducibility. Of course, improved sheet quality from the recently standardized TD-NiCr manufacturing process should improve spotweld reproducibility.

The solid-state spotwelds in SP TD-NiCr look most promising, since the TD-NiCr microstructure was continuous through the weld line. Also, small grains at the weld interface and melted material were avoided. However, much more testing has to be done before a preference can be established.

Resistance Seam Welding

In comparison to the two previously-discussed solid-state welding processes, relatively little work has been previously done in applying resistance seam welding (RSEW) to TD-NiCr sheet. One attempt was reported to fabricate a TD-NiCr corrugation-stiffened heat-shield panel using solid-state RSEW (ref. 9). The particular joint welded was a lap joint between a 0.25 millimeter (0.010 in.) thick corrugation and a 0.4 millimeter (0.015 in.) thick face sheet of TD-NiCr. The particular RSEW process used in this case differs from conventional RSEW in that refractory metal wheel electrodes were used rather than copper electrodes. The refractory electrodes heated the entire thickness of TD-NiCr between them to temperatures below the melting point rather than just the joint interface. Welding was done in an inert atmosphere to prevent oxidation of the electrodes and TD-NiCr. Unfortunately, excessive warpage of the panels occurred due to the localized heating at the areas of contact between the corrugation and face sheet. Thus, this welding attempt was not considered successful.

Evaluation of the solid-state RSEW process for TD-NiCr is continuing under a NASA contract (ref. 4). The welding parameters being used are shown in table 6. These conditions have produced sound, solid-state seam welds free of unwelded areas, cracks, etc. Various TD-NiCr surface preparation methods are being evaluated, as also shown in table 6. The effect of preparations A, B, and C on the microstructure of welds in commercial TD-NiCr is shown in figure 17. As previously described under "Diffusion Welding," smoothing of the surface asperities by 600-grit sanding and removal of the cold worked surface layer by electropolishing (as in preparation C) are effective in eliminating the small, recrystallized grains at the weld interface (fig. 17(c)). A continuous weld line still remains since the microstructure of commercial-grade TD-NiCr is stable up to the melting point and resists grain growth across the weld interface.

The effect of surface preparations B and D (see table 6) on RSE welds in specially processed (SP) TD-NiCr is shown in figure 18. Again, electropolishing (as in preparation D) is effective in eliminating the small, recrystallized grains at the weld interface, while just 600-grit sanding (as in surface preparation B) is not. The patch of small grains evident near the weld line in figure 18(a) may be due to excessive deformation during welding as was described for diffusion welds in SP TD-NiCr. Some trace of the weld line can be seen with surface preparation D (fig. 18b) but considerable grain growth across the weld line has also occurred.

Room temperature and 1090° C (2000° F) tensile-shear testing of 5t overlap RSE welds has always resulted in parent metal failure regardless of the surface preparation used. Evidently the 5t overlap is too large for tensile-shear testing to show the differences in weld quality apparent in figures 17 and 18. Creep-rupture shear tests of 5t overlap RSE welds with surface preparation D at 1170° C (2140° F) again resulted in all parent metal failures.

The initial RSEW results look very encouraging. It appears that parent metal properties can probably be attained with good microstructures. The RSEW process has the attractive feature of being able to make a wide, continuous weld in any lap configuration. This provides large weld areas for extra strength. But problems with panel warpage will have to be solved and more evaluation of RSEW strength must be done before this process can be seriously considered for use with TD-NiCr.

Explosion Welding

Explosion welding (EXW) of TD-NiCr has been attempted in a study reported by Yount (ref. 14). After a postweld high temperature exposure of 1300° C (2375° F) for 15 minutes, a band of small, recrystallized grains formed at the weld line (similar to those described for diffusion and resistance welds). The small grains weakened the joint, and the reported tensile-shear properties were similar to those of braze joints. The base metal was heavily cold worked during explosion welding and also recrystallized after the above heat treatment. This probably weakened the base material. If explosion welding is to be considered in the future, the amount of cold work in the base material and at the interface will have to be reduced so that recrystallization can be avoided.

Roll Welding

Johnson and Killpatrick (ref. 9) also attempted roll welding of TD-NiCr. Ribbed panels were fabricated by roll welding 0.25 millimeter (0.010 in.) thick vertical ribs to 0.3 millimeter (0.012 in.) thick face sheets. The best welds were made at 980° C (1800° F) with a 20 percent reduction per pas for 3 passes. However, rib-cracking was occasionally encountered, and small grains formed at the rib-to-face sheet interface. It was decided that more development work was needed.

Futrue work should be done with better surface preparation as described in this summary to avoid small grains at the weld interface. Also, solid-state welding commercial-grade TD-NiCr with dissimilar metallurgical orientations (e.g., rolling directions crossed at 90° in a lap joint) has resulted in poor joints (ref. 4). This is a preliminary finding and will be more fully explored. However, this could be a problem in roll welding T-joints since they usually involve dissimilar orientations.

Results of Brazing Studies

Numerous brazing alloys have been developed and evaluated for TD-NiCr (refs. 11, 13, and 14). Some of the reported braze alloys are listed in table 7. Of the alloys evaluated to date, TD-6 is the most widely preferred and has been used in several types of TD-NiCr components. The TD-6 alloy has shown superior strength and oxidation resistance as compared to the other braze alloys evaluated in the 980° to 1200° C (1800° to 2200° F) range. Also, TD-6 has shown less erosion of TD-NiCr during brazing than many of the other braze alloys.

As seen in table 7, the composition of TD-6 is basically that of Hastelloy C with 4 percent silicon added to depress the melting point and provide a brazing temperature of 1300° C (2375° F). The TD-6 alloy has been used extensively to braze TD-NiCr honeycomb heat shield panels by at least three organizations (refs. 9, 10, and 11). It has also been used to braze some TD-NiCr jet engine components (ref. 13).

The TD-6 alloy has good wetting and adequate flow characteristics at 1300° C (2375° F) on TD-NiCr. However, at this high brazing temperature, significant erosion can take place in thin TD-NiCr components being brazed. Significant metallurgical interaction between TD-6 and TD-NiCr also takes place during elevated temperature exposures in the 980° C to 1200° C (1800° F to 2200° F) range. Porosity often develops at the TD-6/TD-NiCr interface and in the TD-NiCr, and white etching regions, known to be thoria depleted regions (ref. 2), form as shown in figure 19 (ref. 11).

Creep-rupture properties of TD-6 brazements found in the literature are difficult to interpret and compare because the large overlaps and braze areas tested force failure to occur in the parent metal. Some creep-rupture properties for TD-6 lap brazements are shown in figure 20. The 1090° C (2000° F) tests in figure 20 failed mostly in the parent material while the 1200° C (2200° F) tests failed in the braze alloy. It should be pointed out that the TD-6 alloy can not be expected to have greater creep-rupture strength than its basic Hastelloy C composition in the 980° to 1200° C (1800° to 2200° F) temperature range.

We currently are conducting an in-house program to develop an improved brazing alloy for TD-NiCr. Some of the goals of the improved braze alloy program are higher elevated temperature strength, a brazing temperature below 1300° C (2375° F), remelt temperature above 1315° C (2400° F), low erosion of TD-NiCr, minimal metallurgical interaction with TD-NiCr at elevated temperatures, and oxidation resistance comparable to that of TD-NiCr. One approach being used is to reduce or eliminate the elements in the braze alloy that are known to rapidly diffuse into TD-NiCr (such as Si and B) by the use of low-melting, nickel-base eutectics. This program is in its early stages so significant results are not yet available.

We generally prefer welded joints over brazed joints for TD-NiCr. The reason for this is that the introduction of a foreign material (and associated problems such as deleterious metallurgical interactions) can be avoided with welding. Also, it is difficult to find a braze alloy with elevated temperature strength equivalent to TD-NiCr and a lower melting point than TD-NiCr. However, brazing can be useful in applications where the braze area is large enough to compensate for low braze strength and where the braze alloy can be applied thin enough to minimize metallurgical interaction with the TD-NiCr.

Discussion of Current State-of-Technology

Status of Joining Processes

Fusion welding of TD-NiCr has been fairly-well developed, and actual components have been successfully welded. Both EBW and GTAW can provide sound, defect-free welds in TD-NiCr. However, strengths of these joints are generally much lower than that of the parent material. Thus, these joining methods are limited to applications with low-stressed joints.

Diffusion welding has provided very high quality welds in TD-NiCr, but only small-scale specimens have been welded. Since parent metal strength and microstructure can be attained, diffusion welding should be scaled-up to join full-size TD-NiCr components. The principles of diffusion welding described herein should be readily applicable. The main obstacle to scaling-up diffusion welding will probably be fabrication of tooling to provide the intimate contact over the large areas necessary for this process. Work currently being done to lower diffusion welding temperatures should lessen anticipated tooling problems.

Resistance spot welding is well developed in both the fusion and solid-state modes, and high quality, high strength welds can be made. However, there is some hesitation to accept resistance spot welding as a reliable, high-quality joining process for critical applications. Fabrication and extensive testing, including fatigue testing, of full-size components (as well as in-process control and NDE) should be done to prove the reliability of this process. Also, work on improving the fatigue resistance of these joints is needed.

Resistance seam welding is in a preliminary stage of development but has been shown to give good quality welds in TD-NiCr. Because resistance seam welding can yield large area, economical joints, it should be applied to full-size components.

However, the problem with component warpage will have to be solved.

Very little work has been done with either explosion welding or roll welding, and preliminary results do not look encouraging. Major improvements are needed in both of these processes before they can be seriously considered for use with TD-NiCr components.

Sound braze joints can be made with the TD-6 alloy. Thus, the joining method has been widely-used in a variety of applications. However, degradation of brazed joints (e.g., formation of porosity and thoria-free zones in TD-NiCr) occurs during high temperature exposure. Also, the TD-6 alloy, itself, is not very strong at elevated temperatures. Work is being done to develop a better braze alloy for TD-NiCr, but this is a difficult assignment due to the stringent and conflicting requirements imposed (e.g., low brazing temperature, high remelt temperature, and minimal interaction with TD-NiCr).

Comparison of Joining Processes for Typical Applications

At the current state-of-technology, some preliminary comparisons can be made of the joining processes covered in this summary. These comparisons can only be drawn from results existing to date. Since work is continuing, future results may have a great influence on these comparisons.

It is obvious from the data shown in this summary that spotwelds have tremendous potential as a high strength welding technique for TD-NiCr. The solid-state spotwelds in specially-processed TD-NiCr show the greatest potential since the TD-NiCr microstructure is unchanged and parent metal properties should result. However, the fusion and solid-state spotwelds in commercial-grade TD-NiCr are also promising since both have shown exceptionally good properties to date. More extensive testing of spotwelds is needed, in general, to prove their worth. But, at this time, resistance spotwelds are much easier and economical to make than diffusion welds. Thus, the resistance spot welding process is probably a better choice than diffusion welding for making lap joints in TD-NiCr sheet. Resistance spot welding should seriously be considered for such applications as TD-NiCr heat shields. Resistance seam welding is also a candidate for fabricating heat shields, but it is at a much earlier stage of development.

Diffusion welding is a logical choice for joining heavier sections of TD-NiCr where resistance spot welding is not applicable. Some examples are airfoil shapes, such as air-cooled turbine blades and other jet engine components. It has been shown that diffusion welds produces very high quality welds with parent metal properties.

Brazing is the most easily applied joining process to the fabrication of honeycomb panels and other structures involving T-joints. Brazing can be more forgiving of small misalinements than diffusion welding. Also, it is more applicable to some joint configurations (such as T-joints) than resistance welding. Of course, the problems described in this summary concerning brazing have to be considered for each application.

Fusion welding has the advantages over other joining processes of being economical, easily applied, and not limited in thickness or joint configuration. In noncritical applications where high temperatures are not encountered, fusion welding may be the best choice.

Concluding Remarks

As seen in this summary, there are many joining processes that can be used to make sound welds in TD-NiCr. Some of these are electron beam welding (EBW), gas-tungsten arc welding (GTAW), diffusion welding (DFW), resistance spot welding (RSW), resistance seam welding (RSEW), and brazing. The strengths of the welds made by the various processes show considerable variation, especially at elevated temperatures. Most of the processes involving fusion tend to give weak welds at elevated temperatures (with the exception of fusion-type resistance spotwelds). However, solid-state welds have been made with parent metal properties.

The particular process used for any specific application will, of course, be dictated by the specific joint requirements. For example, if a particular joint will never be highly stressed at elevated temperatures, fusion welding processes may be satisfactory. But for more highly-stressed joints, one of the solid-state welding methods will probably be required. In applications where high reliability is of paramount importance, DFW, RSW, and RSEW offer the most promise.

More work is needed to develop and evaluate DFW, RSW, RSEW, and brazing for joining TD-NiCr. Efforts in this direction are being carried out at General Dynamics/Convair (under a NASA contract) and at NASA-Lewis. Only after these processes are completely evaluated can they be finally compared for high temperature applications.

References

1. C. P. Blankenship and N. T. Saunders: NASA TM X-68024, Mar. 1972.

2. Unpublished NASA-Lewis Research Center data.

3. Unpublished results of General Dynamics/Convair Aerospace Division personnel under NASA Contract NAS3-15567.

4. Unpublished results of International Harvester/Solar Aircraft Division personnel under NASA Contract NAS3-15567.

5. L. J. Klinger, W. R. Weinberger, S. Baranow, and P. G. Bailey: NASA CR-120796, Part I, May 1972.

6. Unpublished Boeing Co. results.

7. K. H. Holko: NASA TM X-52952, Jan. 1971.

8. K. H. Holko and T. J. Moore: Welding J. Res Suppl., 1972, vol. 51, p. 81s.

9. R. Johnson, Jr. and D. H. Kilpatrick: McDonnell-Douglas Astronautics Co. (AFFDL-TR-68,130, PT. I, AD-843067), July 1968.

10. E. J. Rupert: Martin-Marietta Corp. (AFFDL-TR-68-129 Vol. 4) Mar. 1970.

11. W. D. Brentnall, A. R. Stetson, and A. G. Metcalfe: Solar Division, International Harvester (AFML-TR-68-299), Oct. 1968.

12. S. R. Carpenter: Rep. GDC-ERR-1458, General Dynamics Corp., 1969.

13. R. E. Yount, R. E. Kutchera, and D. L. Keller: Rep. R67FPD396, General Electric Co. (AFML-TR-67-224, DDC No. AD-824209), Oct. 1967.

14. R. E. Yount: SAMPE Proceedings, Vol. 14, Western Periodicals Co., 1968, Article II-2B-1.

APPENDIX - Reported resistance spot welding parameters and properties of tensile shear single-spot lap welds in TD-NiCr sheet.

SHEET THICKNESS, MM (IN.)	SPOT DIAM MM (IN.)	TYPE OF WELD	SURFACE PREPARATION	MACHINE TYPE	ELECTRODES		PNEUMATIC FORCE, KN (LBS)	WELDING CURRENT, KA	MACHINE SETTINGS				TENSILE-SHEAR PROPERTIES						REFERENCES
													RT		1090° C (2000° F)		1200° C (2200° F)		
					CLASS	CONTACT FACE			PERCENT HEAT	WELD CYCLES	COOL CYCLES	NO. OF PULSES	LOAD, KN (LBS)	SHEAR STRESS, MN/m² (KSI)	LOAD, KN (LBS)	SHEAR STRESS, MN/m² (KSI)	LOAD, KN (LBS)	SHEAR STRESS, MN/m² (KSI)	
0.84 (0.033)	5.8 (0.23)	SOLID-STATE	--------------	THREE PHASE	III	20.3 CM (12 IN.) RADIUS	13.4 (3000)	----	37	10	1.5	12	8.46 (1900)	310 (45.0)	-----	-----	1.10 (250)	41.4 (6.0)	12
0.25 (0.010)	2.7 (0.11)	FUSION	WIPE WITH SOLVENT	THREE PHASE†		10 CM (6 IN.) RADIUS	4.45 (1000)	35.0	65	2	---	1	1.31 (294)	210 (30.6)	-----	-----	-----	-----	
0.63 (0.025)	6.3 (0.25)	SOLID-STATE	200 GRIT, DE-GREASE ACETONE WIPE	THREE PHASE	II	6.4 MM (1/4 IN.) FLAT	8.90 (2000)	18.9	27	3.5	2.5	40	6.09 (1370)	190 (27.5)	0.83 (187)	31.8 (4.6)	0.70 (158)	25.7 (3.7)	13, 14
1.0 (0.040)	6.8 (0.27)				II	8.0 MM (5/16 IN.) FLAT	13.4 (3000)	25.9	37	3.5	2.5	42	9.30 (2092)	292 (42.2)	1.08 (242)	29.7 (4.3)	0.97 (218)	24.8 (3.6)	
0.63 (0.025)	4.8 (0.19)			SINGLE PHASE	III	20.3 CM (8 IN.) RADIUS	2.45/6.67 (550/1500)	14.3	65	2	1	60	3.54 (795)	192 (27.8)	0.25 (55)	13.8 (2.0)	-----	-----	
1.0 (0.040)	4.8 (0.19)						2.22/7.11 (500/1600)	16.3	70				4.59 (1032)	259 (37.5)	0.42 (94)	22.8 (3.3)	-----	-----	
0.63 (0.025)	4.8 (0.19)	FUSION					2.67/7.11 (600/1600)	15.7	70				4.96 (1114)	247 (35.8)	0.65 (146)	33.1 (4.8)	-----	-----	
1.0 (0.040)	5.8 (0.23)						2.67/7.11 (600/1600)	17.4	75				8.65 (1944)	323 (46.9)	1.05 (235)	40.0 (5.8)	-----	-----	
1.5 (0.060)	6.6 (0.26)						2.67/7.11 (600/1600)	22.1	95				12.1 (2710)	343 (49.7)	1.23 (277)	35.2 (5.1)	-----	-----	
0.51 (0.020)	4.1 (0.16)		WIPE WITH SOLVENT CLEANER	THREE PHASE	---	----------------	8.90 (2000)	----	27	7	0.5	1	4.09 (920)	318 (46.0)	0.45 (100)	34.5 (5.0)	0.33 (75)	25.5 (3.7)	9
0.51 (0.020)	4.3 (0.17)	SOLID-STATE	NO. 1 EMERY PAPER, ACETONE WIPE	SINGLE PHASE	---	----------------	6.68 (1500)	----	40	7	0.5	50	-----	------	-----	-----	-----	-----	
0.38 (0.015)	4.4 (0.17)	FUSION	PICKLED, STORE IN FREON		III	20.3 CM (8 IN.) RADIUS	10.0 (2250 LBS)	28.0	28	1	---	1	3.15 (708)	208 (30.1)	0.65 (146)	42.8 (6.2)	-----	-----	2
	5.5 (0.22)	SOLID-STATE				30.5 CM (12 IN.) RADIUS		24.2	< 20	15	---	1	3.32 (745)	141 (20.4)	0.57 (128)	23.5 (3.4)	-----	-----	
0.38* (0.015)	5.4 (0.21)							20.1	< 20	8	---	1	-----	------	-----	-----	-----	-----	

*SPECIALLY PROCESSED (UNRECRYSTALLIZED) SHEET, POSTHEATED AFTER WELDING.

†ONLY TWO OF THE THREE PHASES WERE USED FOR WELDING.

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Table 1. Summary of reported fusion welding results for TD-NiCr sheet.

WELDING PROCESS	MATERIAL THICKNESS		CONFIGURATION	FILLER MATERIAL USED	AVERAGE ULTIMATE TENSILE STRENGTH[a]								REFERENCE
					ROOM TEMP.		650° C (1200° F)		870° C (1600° F)		1090° C (2000° F)		
	MM	IN.			MN/m^2	KSI	MN/m^2	KSI	MN/m^2	KSI	MN/m^2	KSI	
ELECTRON BEAM	0.3	0.010	SIMPLE BUTT,	NONE	710	103	310	45	96	14	34	5	9
ELECTRON BEAM	0.3	0.010	BURN-DOWN FLANGE	TD-NiCr	764	111	---	--	--	--	--	-	9
GAS TUNGSTEN ARC	0.3	0.010	SIMPLE BUTT	NONE	---	---	---	--	--	--	--	-	9
GAS TUNGSTEN ARC	0.5	0.018	SIMPLE BUTT - ONE PASS	HASTELLOY X[b]	537	78	---	--	--	--	--	-	10
				INCONEL 62[c]	516	75	---	--	--	--	--	-	
GAS TUNGSTEN ARC	1.6	0.060	SIMPLE BUTT, DOUBLE BEVEL - TWO PASSES	HASTELLOY X	770	112	---	--	--	--	--	-	10
				INCONEL 62	654	95	---	--	--	--	--	-	

[a]ALL FAILURES WERE IN THE FUSION ZONE OF THE WELD FOR ULTIMATE TENSILE STRENGTHS SHOWN.
[b]HASTELLOY X: Ni-22Cr-19Fe-9Mo-1.4Co-0.7Si-0.5Mn-0.4W
[c]INCONEL 62: Ni-16Cr-8Fe-2.4Cb-0.1Si

Table 2. Diffusion welding parameters reported for TD-NiCr sheet.

MATERIAL CONDITION	MATERIAL THICKNESS		JOINT CONFIGURATION	HEAT SOURCE	WELDING PARAMETERS					REFERENCE
					TEMPERATURE		TIME (HRS)	PRESSURE		
	MM	IN.			$^\circ$C	$^\circ$F		MN/m^2	KSI	
COMMERCIAL-GRADE	0.08/0.25	0.003/0.010	T-JOINT	HOT PRESS	1315	2400	1.5	2.7	0.4	9
	"	"	"	" "	1200	2200	11.5	2.7	0.4	"
COMMERCIAL-GRADE	0.25	0.010	LAP JOINT	DIRECT RESIS-TANCE HEATING	1150	2100	0.006	69	10	11
COMMERCIAL-GRADE AND SPECIALLY-PROCESSED	1.5	0.060	LAP JOINT	HOT PRESS	705/1190	1300/2175	1.0/2.0	210/14	30/2	8
SPECIALLY-PROCESSED	0.25	0.010	LAP JOINT	HOT PRESS	760	1400	1.0	210	30	2

Table 3. Average tensile-shear strengths of diffusion welds in TD-NiCr sheet at 1090° C (2000° F) in air. Values shown are averages of two or more tests (ref. 8).

MATERIAL TYPE	SHEAR STRESS		LOCATION OF FRACTURE
	MN/m^2	KSI	
PARENT METAL	65.1	9.5	PARENT METAL
SPECIALLY-PROCESSED	51.4	7.3	PARENT METAL
COMMERCIAL-GRADE	39.7	5.8	WELD LINE

Table 4. Summary of thicknesses of TD-NiCr sheet fusion and solid-state spotwelded. Complete welding parameters and spotweld strengths are shown in the Appendix.

MATERIAL THICKNESS		SPOT DIAMETER		MACHINE TYPE USED	REFERENCE
MM	IN.	MM	IN.		
(a) FUSION SPOTWELDS.					
0.38	0.015	4.4	0.170	SINGLE PHASE	2
0.63	0.025	4.8	0.190	↓	13, 14
1.0	0.040	5.8	0.230	↓	↓
1.5	0.060	6.6	0.260	↓	↓
0.25	0.010	2.7	0.110	THREE PHASE	12
0.51	0.020	4.1	0.160	↓	9
0.08	0.003	---	-----	--------------	9
(b) SOLID-STATE SPOTWELDS.					
0.38	0.015	5.5	0.22	SINGLE PHASE	2
0.38[a]	0.015	5.4	0.21	↓	2
0.51	0.020	4.3	0.17	↓	9
0.63	0.025	4.8	0.19	↓	13, 14
1.0	0.040	4.8	0.19	↓	↓
0.63	0.025	6.3	0.25	THREE PHASE	↓
0.84	0.033	5.8	0.23	↓	12
1.0	0.040	6.8	0.27	↓	13, 14

[a]SPECIALLY-PROCESSED (UNRECRYSTALLIZED) MATERIAL, RECRYSTALLIZED AFTER SPOTWELDING.

Table 5. 100-Hour creep-rupture shear strengths for single-spot lap joints in resistance spotwelded TD-Ni-Cr sheet.

SHEET THICKNESS MM (IN.)	TYPE OF WELD	100-HOUR CREEP-RUPTURE-STRENGTHS				REFERENCE
		1090^0 C (2000^0 F)		1200^0 C (2200^0 F)		
		LOAD, N (LBS)	STRESS, N/m^2 (KSI)	LOAD, N (LBS)	STRESS, N/m^2 (KSI)	
0.63 (0.025)	SOLID	702 (158)	23 (3.3)	565 (127)	18 (2.6)	13
1.0 (0.040)	STATE[a]	610 (137)	16 (2.3)	388 (87)	10 (1.5)	13
0.5 (0.020)	FUSION[a]	400 (90)	31 (4.5)	--------	-------	9
0.5 (0.020)	SOLID STATE[b]	258 (58)	17 (2.5)	--------	-------	9
0.38 (0.015)	FUSION[b]	423 (95)	27 (3.9)	--------	-------	2
	SOLID STATE[b]	506 (114)	23 (3.4)	--------	-------	2

[a]THREE-PHASE RESISTANCE WELD.

[b]SINGLE-PHASE RESISTANCE WELD.

Table 6. Conditions used for solid-state resistance seam welding TD-NiCr sheet (ref. 4).

MATERIAL: 0.25 MILLIMETER (0.010) THICK COMMERCIAL-GRADE AND SPECIALLY-PROCESSED TD-NiCr SHEET

OVERLAP: NOMINALLY 5 t

ELECTRODES: MOLYBDENUM, THICKNESS GREATER THAN OVERLAP

SQUEEZE FORCE: 1,380 N (310 LBS)

CURRENT: 60 AMPERES

WELDING SPEED: 20 CENTIMETERS/MINUTE (8 IN./MIN)

WELD TEMPERATURE: 1315^0 C (2400^0 F) - ESTIMATED

ATMOSPHERE: ARGON

DEFORMATION: 0 TO 4 PERCENT

SURFACE PREPARATIONS BEING EVALUATED:

A - AS-RECEIVED; HOT ALKALINE DEGREASE; DEIONIZED WATER/AIR BLAST RINSE, WARM AIR DRY

B - ABRADE THROUGH 600-GRIT PAPER (WELD SIDE ONLY); RINSE DEIONIZED WATER/AIR BLAST; WARM AIR DRY

C - PREPARATION B PLUS ELECTROPOLISH IN SUMMA SOLUTION (25^0 TO 40^0 C (80^0 TO 100^0 F), 8 VOLTS, 1.5 MIN); RINSE DEIONIZED WATER/AIR BLAST; WARM AIR DRY

D - PREPARATION A PLUS ELECTROPOLISH IN SUMMA SOLUTION AS ABOVE

Table 7. Some of the braze alloys evaluated for TD-NiCr (refs. 11 and 14).

ALLOY DESIGNATION	ESTIMATED BRAZING TEMPERATURE °C (°F)	NOMINAL CHEMICAL COMPOSITION - WEIGHT %									
		Ni	Cr	Pd	Si	B	Au	Mo	W	Fe	Co
TD-5	1315 (2400)	BAL	22	--	4	---	--	9	-	22	1.5
TD-6	1300 (2375)	BAL	16	--	4	---	--	17	5	4-7	---
TD-20	1300 (2375)	BAL	16	--	4	---	--	25	5	---	---
Ni-Pd	1245 (2275)	BAL	--	60	---	---	--	--	-	---	---
J8100	1175 (2150)	BAL	19	--	10	---	--	--	-	---	---
PALNIRO 1	1175 (2150)	25	--	25	---	---	50	--	-	---	---
AMS 4779 (CM50)	1065 (1950)	BAL	--	--	3.5	1.9	--	--	-	---	---
PALNIRO 7	1065 (1950)	22	--	9	---	---	70	--	-	---	---
TD-50	1175 (2150)	BAL	20	--	10	---	--	9	-	21	2.0 MAX
NX77	1190 (2175)	BAL	5	--	7	1	--	--	1	---	1
NSB	1290 (2350)	BAL	--	--	2	0.8	--	--	-	---	---

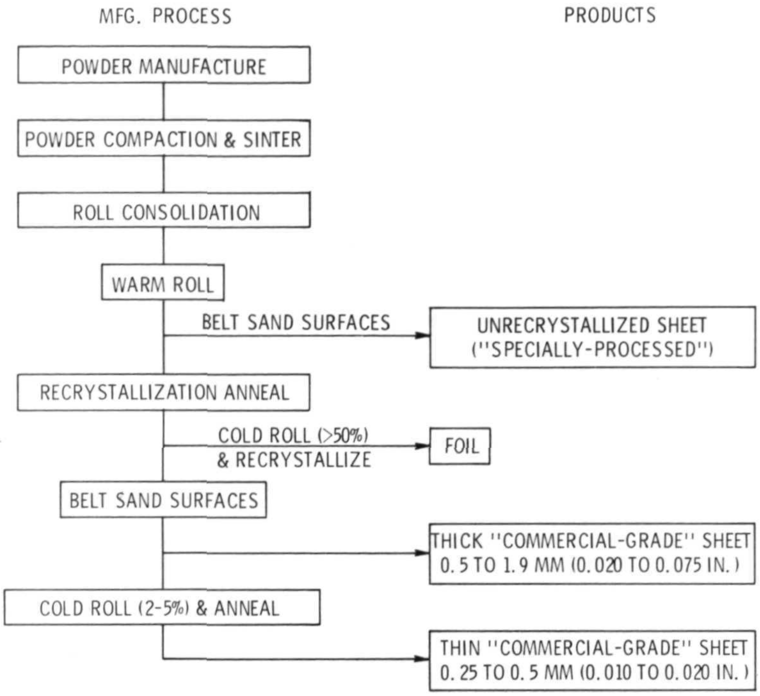

Figure 1. - Manufacturing process for TD-NiCr sheet and foil.

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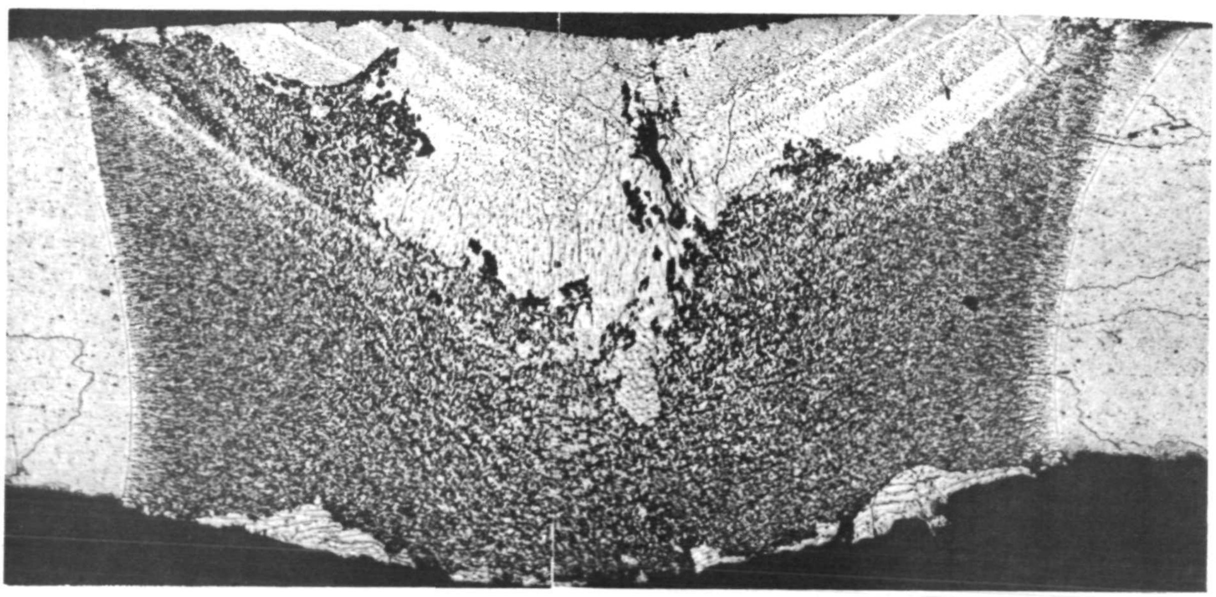

Figure 2. - Typical electron beam weld in 0.25 mm (0.010 in.) thick commercial-grade TD-NiCr (ref. 6). No filler material was used. Etchant, 100 ml. H_2O, 2 g. Cr_2O_3 and 10 ml. H_2SO_4 (electrolytic, 3 V dc). X250.

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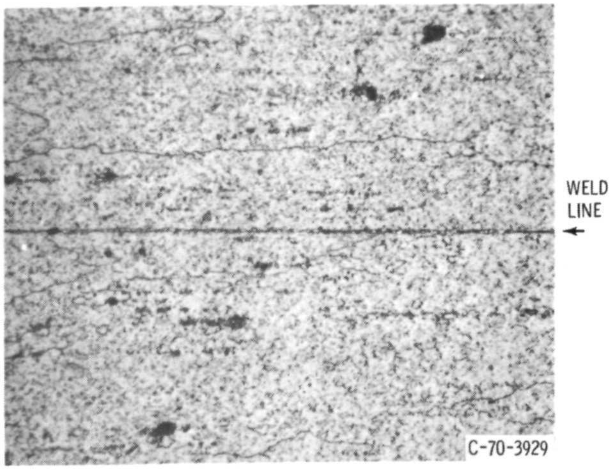
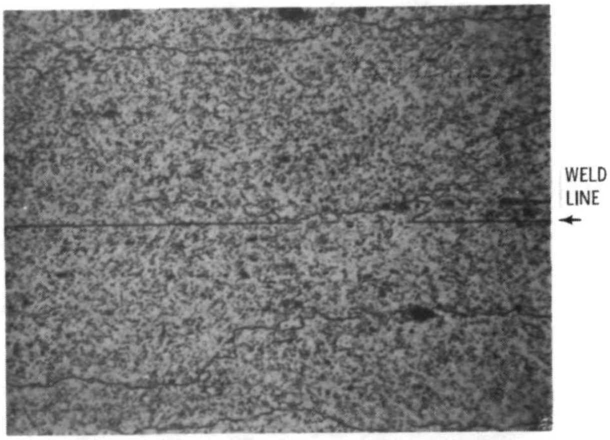
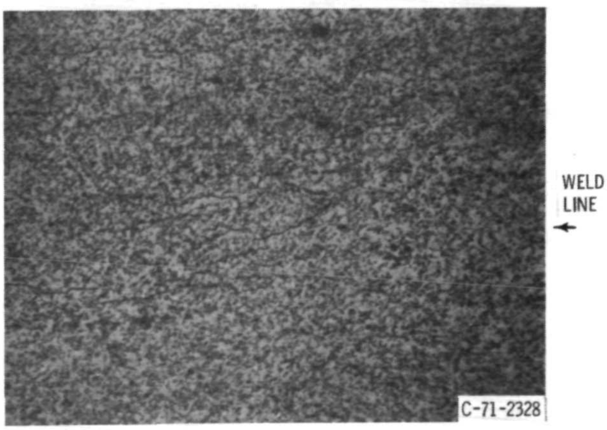


(a) COMMERCIAL-GRADE MATERIAL WITH 600-GRIT SANDED SURFACE PREPARATION.



(b) COMMERIAL-GRADE MATERIAL WITH ELECTROPOLISHED SURFACE PREPARATION.



(c) SPECIALLY PROCESSED MATERIAL WITH ELECTROPOLISHED SURFACE PREPARATION.

Figure 3. - Microstructures of diffusion welded TD-NiCr sheet with two-step weld cycle and different surface preparations and starting material conditions. Sections were taken parallel to rolling direction. Etchant, 100 ml. H_2O, 2 g. CrO_3 and 10 ml. H_2SO_4 (electrolytic, 3 V dc). X500.

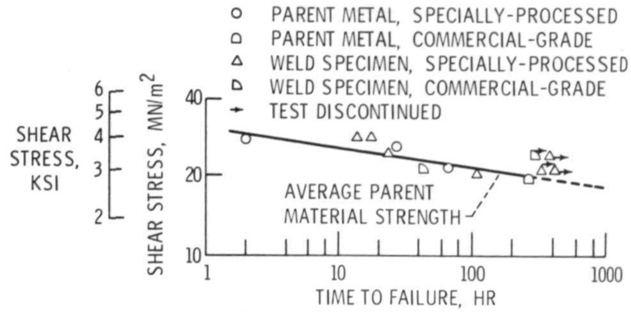


Figure 4. - Results of creep-rupture shear testing of parent and diffusion welded lap joints in 1.6 millimeter (0.060-in.) TD-NiCr sheet at 1090° C (2000° F) in air. (All samples annealed at 1260° C (2300° F) for 1 hour prior to test.)

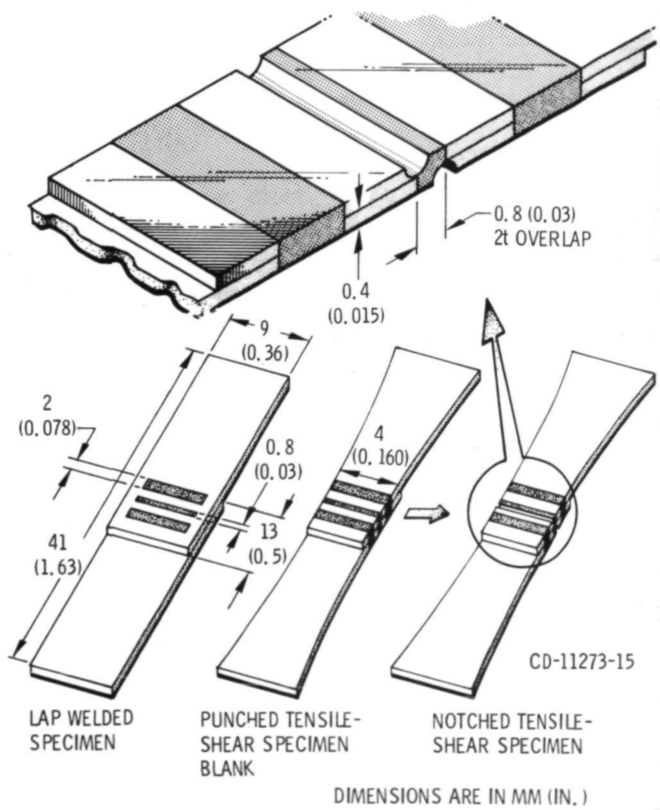


Figure 5. - Configuration of tensile-shear specimens used to evaluate diffusion welds in TD-NiCr sheet.

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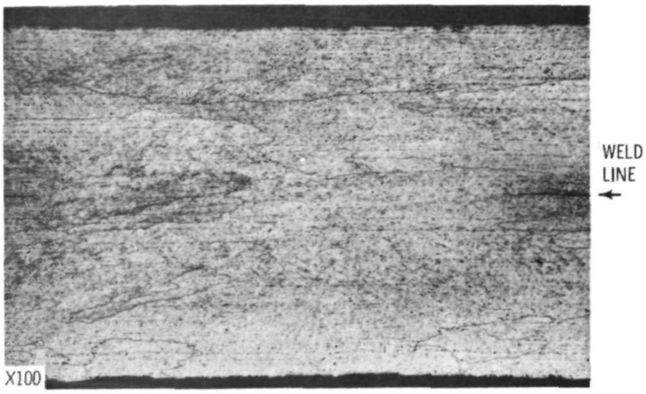
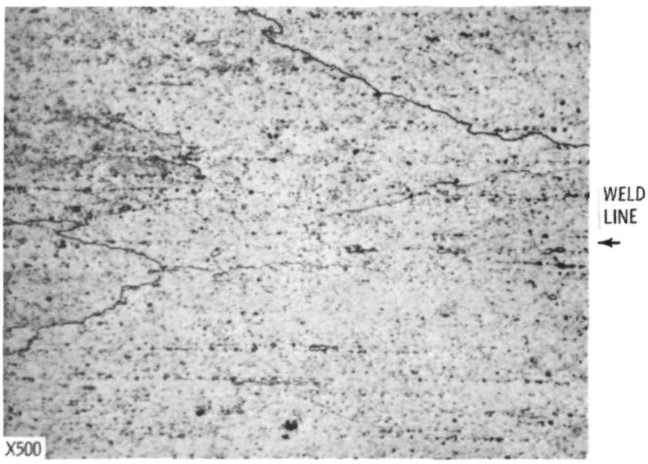
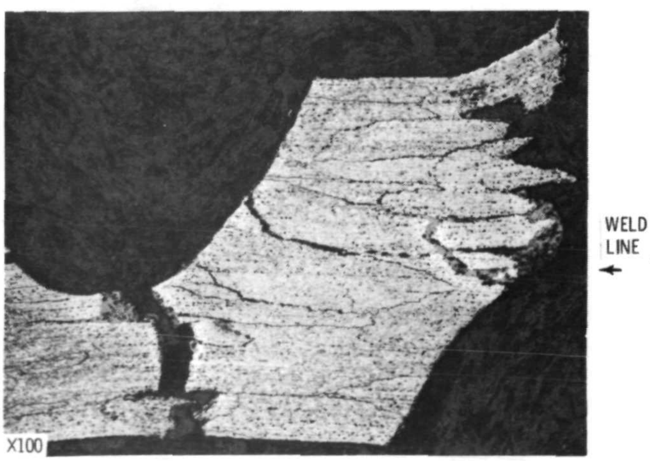


(a) DIFFUSION WELD CROSS-SECTION.



(b) ENLARGEMENT OF CROSS-SECTION IN (a).



(c) WELD IN (a) NOTCHED AND CREEP-RUPTURE TESTED AT 1090° C (2000° IN AIR. SPECIMEN FAILED IN PARENT MATERIAL AFTER 24 HOURS AND A TENSILE STRESS OF 34.5 MN/m^2 (5 ksi). WELD WAS STRESSED IN SHEAR AT 17.2 MN/m^2 (2.5 ksi).

Figure 6. - Microstructures of a typical diffusion weld in specially processed TD-NiCr sheet after a recrystallization heat treatment of 1180° C (2150° F)/ 2 hours/H_2.

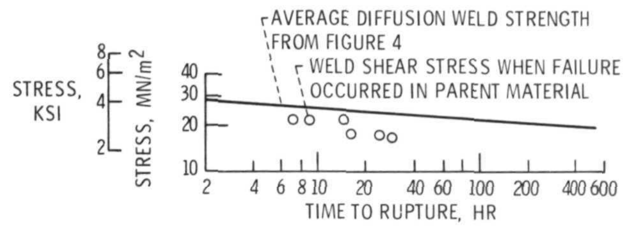


Figure 7. - Results of creep-rupture shear testing of diffusion lap welds (2t overlap) in 0.4 mm (0.015 in.) specially-processed TD-NiCr sheet. All failures were in the parent material. Testing was conducted at 1090^o C (2000^o F) in air.

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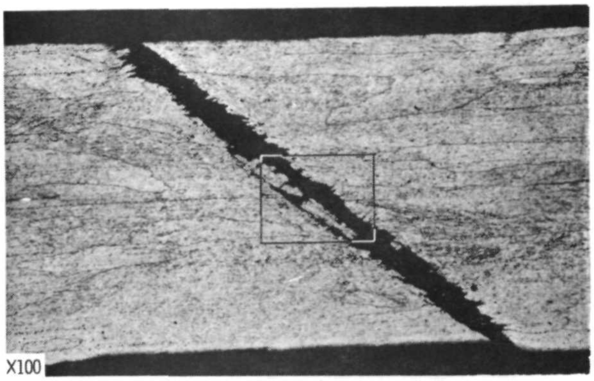
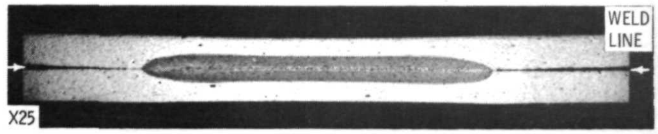


(a) HOT PRESS WELD CROSS-SECTION.

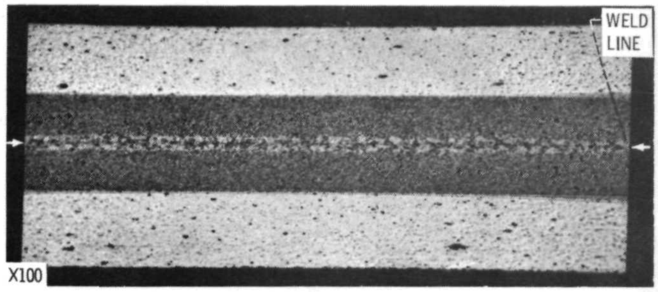
(b) ENLARGEMENT OF CROSS-SECTION IN (a).

(c) WELD IN (a) (VIEW OF OPPOSITE SIDE) NOTCHED FOR CREEP-RUPTURE TESTING. SPECIMEN FAILED AT SMALL GRAINS WHILE HEATING TO TEMPERATURE.

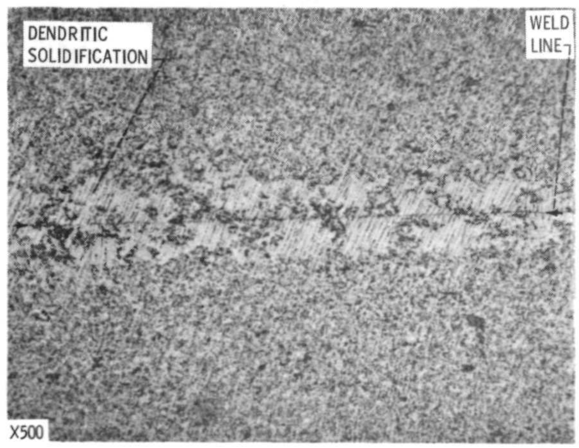
Figure 8. - Effect of excessive deformation on a diffusion weld in specially-processed TD-NiCr sheet after a recrystallization heat treatment of 1180° C (2150° F)/2 hours/H_2.



(a) PHOTOMACROGRAPH OF SPOTWELD CROSS-SECTION.



(b) PHOTOMICROGRAPH FROM CENTER OF SPOTWELD IN (a).



(c) HIGHER MAGNIFICATION PHOTOMICROGRAPH FROM CENTER OF (b).

Figure 9. - Cross-section of typical fusion resistance spotweld in commercial-grade TD-NiCr sheet (ref. 3). Etchant: 10 percent oxalic acid, electrolytic.

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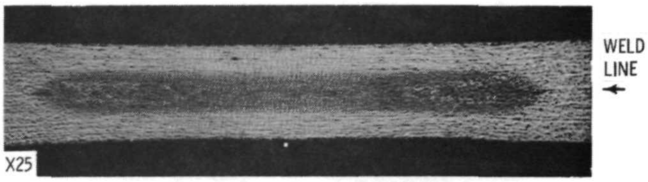
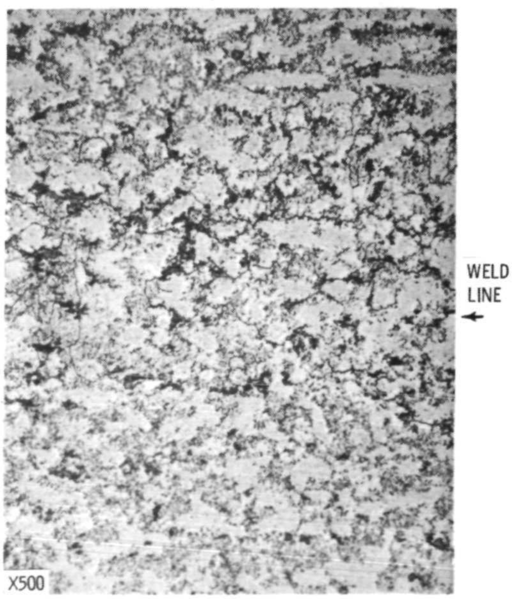


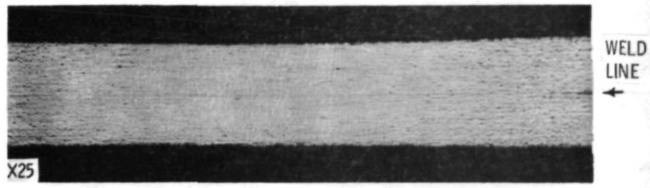
(a) PHOTOMACROGRAPH OF SPOTWELD CROSS-SECTION.

(b) PHOTOMICROGRAPH FROM CENTER OF SPOTWELD IN (a).

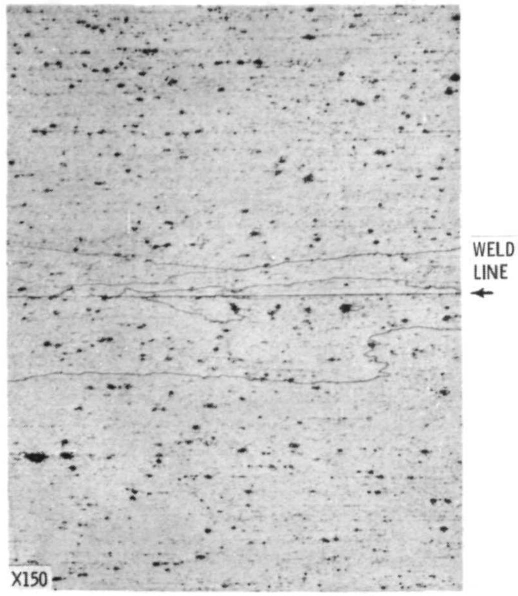


(c) HIGHER MAGNIFICATION PHOTOMICROGRAPH FROM CENTER OF (b).

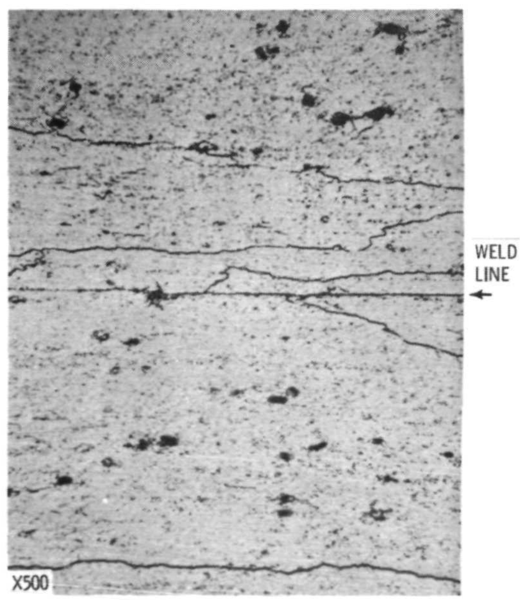
Figure 10. - Cross-section of fusion resistance spotweld in commercial-grade TD-NiCr sheet. Etchant, 100 ml. H_2O, 2 g. Cr_2O_3, 10 ml. H_2SO_4 (electrolytic 3 V dc.).



(a) PHOTOMACROGRAPH OF SPOTWELD CROSS-SECTION.



(b) PHOTOMICROGRAPH FROM CENTER OF SPOTWELD IN (a).



(c) HIGHER MAGNIFICATION PHOTOMICROGRAPH FROM CENTER OF (b).

Figure 11. - Cross-section of typical solid-state resistance spotweld in commercial-grade TD-NiCr sheet with surfaces prepared by chemical polishing. Etchant, 100 ml. H_2O, 2 g. Cr_2O_3, 10 ml. H_2SO_4 (electrolytic, 3 V dc.).

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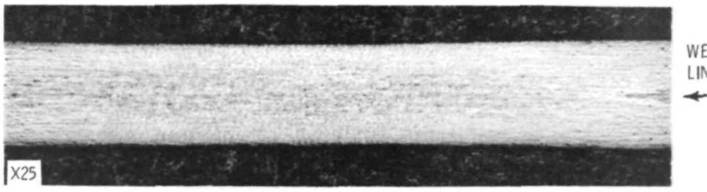
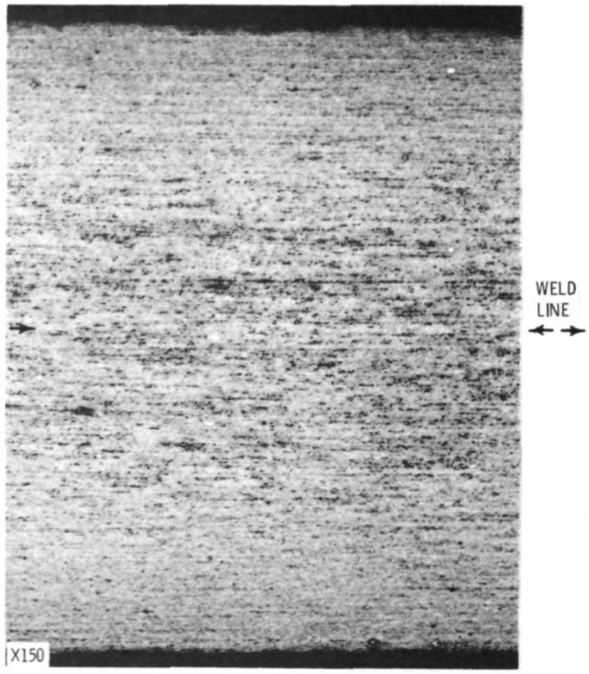
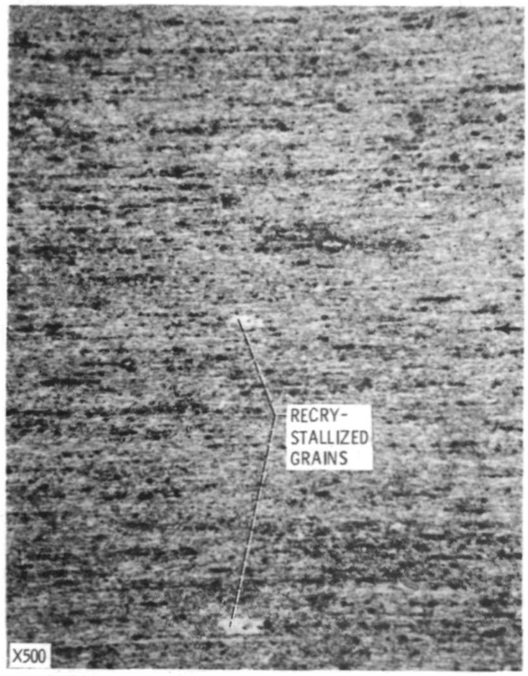


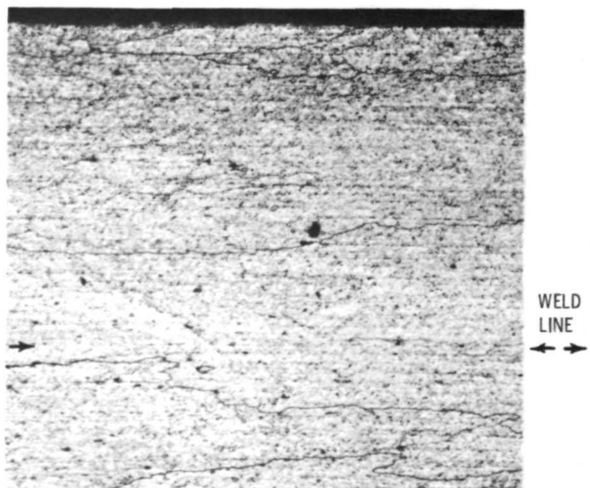
(a) SPOTWELD CROSS-SECTION IN THE AS-WELD CONDITION.



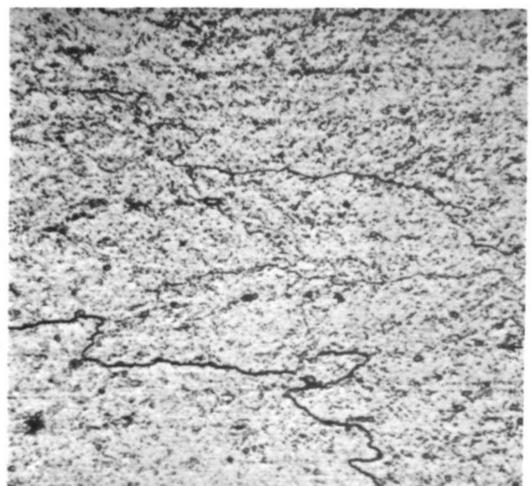
(b) PHOTOMICROGRAPH FROM CENTER OF SPOTWELD IN (a), AS-WELDED.



(c) HIGHER MAGNIFICATION PHOTOMICROGRAPH OF (b), AS-WELDED.



(d) PHOTOMICROGRAPH FROM CENTER OF SPOTWELD AFTER A RECRYSTALLIZATION HEAT TREATMENT.



(e) HIGHER MAGNIFICATION PHOTOMICROGRAPH OF SPOTWELD AFTER RECRYSTALLIZATION HEAT TREATMENT.

Figure 12. - Cross-section of a promising solid-state spotweld in specially-processed TD-NiCr sheet shown in the as-welded condition and after a postweld recrystallization heat treatment of 1200° C (2200° F)/2 hours/H_2. Etchant, 100 ml. H_2O, 2 g. Cr_2O_3, 10 ml. H_2SO_4 (electrolytic, 3 V dc).

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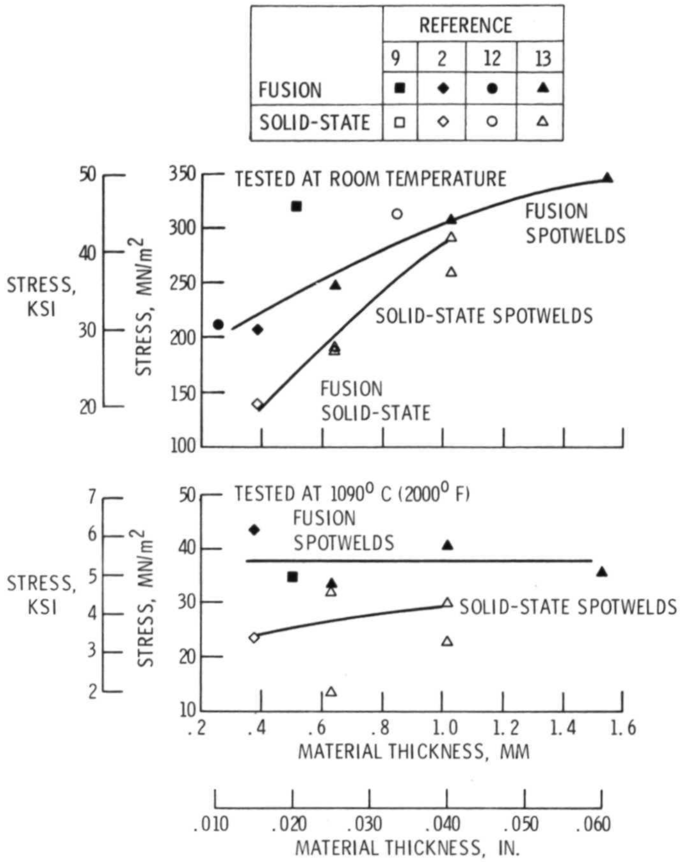

Figure 13. - Effect of material thickness on spotweld tensile-shear strength of TD-NiCr sheet.

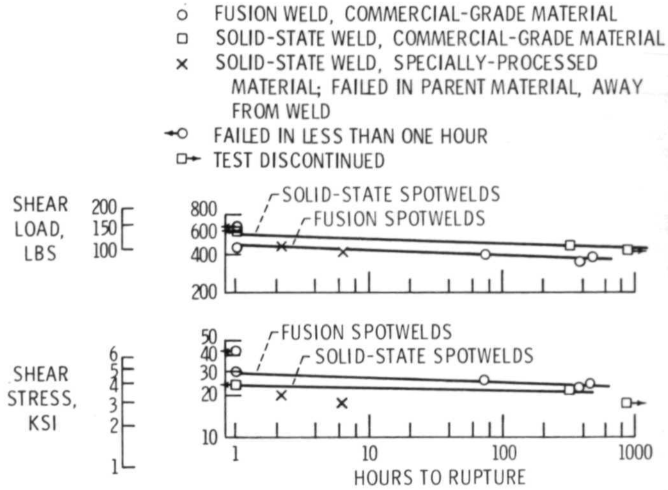

Figure 14. - Results of 1090° C (2000° F) creep-rupture shear tests on resistance spot-welded TD-NiCr sheet.

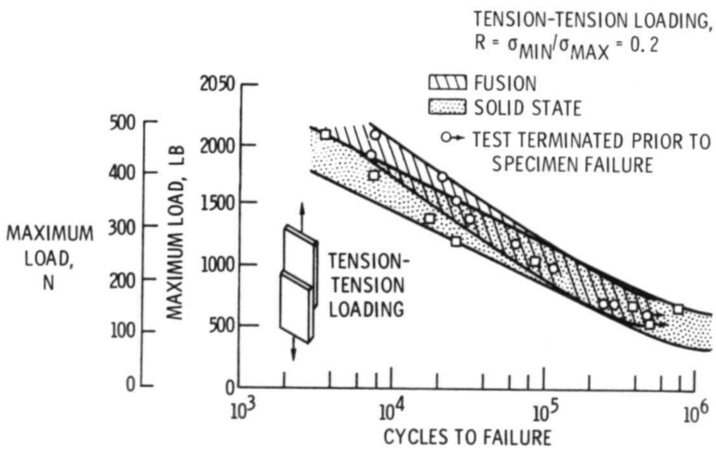

Figure 15. - Room temperature fatigue strength of single-spot resistance spotwelds in 0.5 mm (0.020 in.) TD-NiCr sheet (ref. 9).

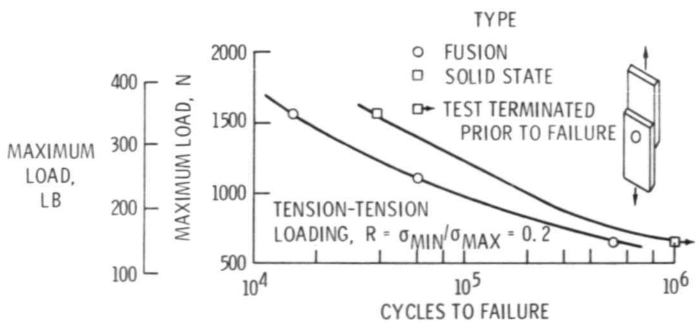

Figure 16. - Room temperature fatigue strength of single-spot resistance spotwelds in 0.4 mm (0.015 in.) TD-NiCr sheet.

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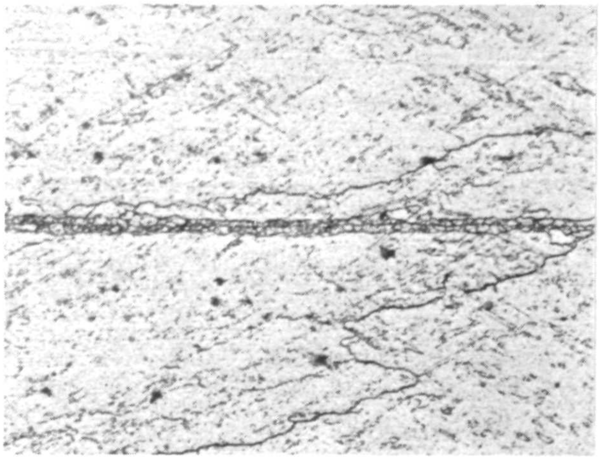
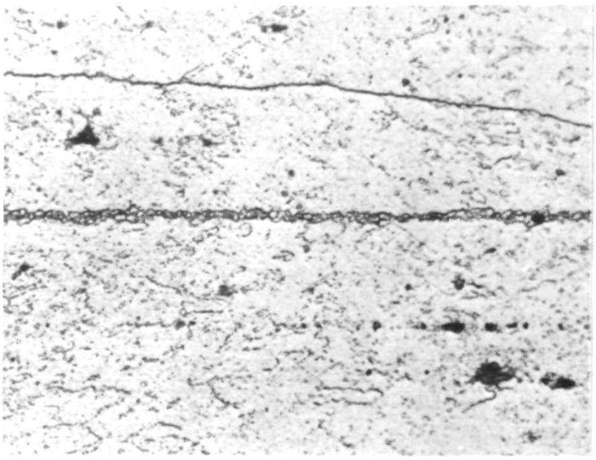
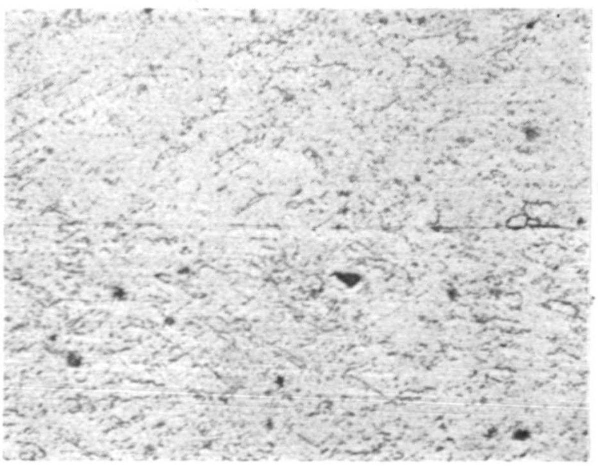


(a) SURFACE PREPARATION A. ALKALINE DEGREASE; DEIONIZED WATER/ AIR BLAST; RINSE: WARM AIR DRY.

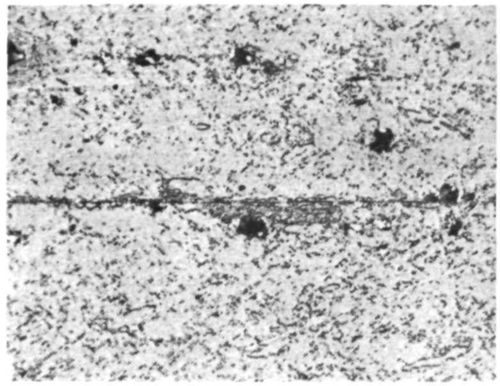


(b) SURFACE PREPARATION B. ALKALINE DEGREASE; TAP WATER RINSE; ABRADE THROUGH 600 GRIT EMERY PAPER; RINSE: DEIONIZED WATER/ AIR BLAST; WARM AIR DRY.

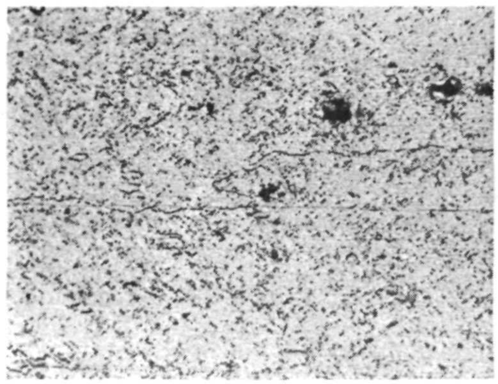


(c) SURFACE PREPARATION C. PREPARATION B PLUS: ELECTROPOLISH IN SUMMA SOLUTION (80 TO 100° F, 8 VOLTS, 1.5 MINUTES); RINSE: DEIONIZED WATER/AIR BLAST; WARM AIR DRY.

Figure 17. - Microstructures of resistance seam-welded lap joints in 0.25 mm (0.010 in.) thick commercial-grade TD-NiCr sheet showing effect of various preweld surface treatments. Etchant, 10 percent oxalic acid; electrolytic (ref. 4). X1000.



(a) SURFACE PREPARATION B. (ABRADE THROUGH 600 GRIT PAPER).



(b) SURFACE PREPARATION D. (SURFACE PREPARATION A PLUS ELECTROPOLISH).

Figure 18. - Microstructures of resistance seam lap welds in specially-processed 0.25 mm (0.010 in.) thick TD-NiCr sheet showing the effect of surface preparation on structure of weld line. Welds were recrystallized at 1170° C (2150° F)/2 hours/H_2 after welding. Etchant, 10 percent oxalic acid, electrolytic. X1000. (Ref. 4.)

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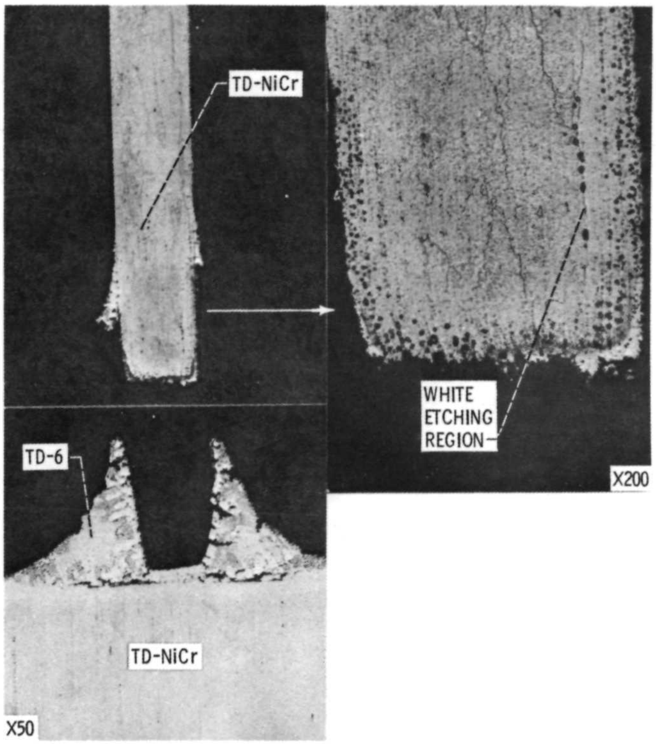
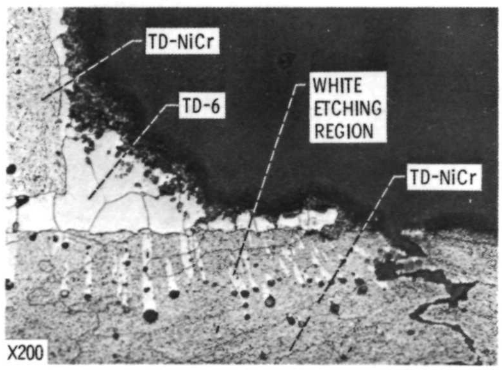


(a) BRAZE JOINT FAILURE IN TD-6/TD-NiCr, CREEP-RUPTURE TESTED AT 13.8 MN/m^2 (2 ksi) PARENT METAL STRESS (UPPER MEMBER), 1200° C (2200° F). JOINT FAILED AFTER 2.15 HOURS.



(b) TD-6/TD-NiCr BRAZE JOINT AFTER 100 HOURS AT 1200° C (2200° F) AND 1200° C (2200° F) BURST TEST.

Figure 19. - TD-6/TD-NiCr braze joints after elevated temperature exposures. (Ref. 11.)

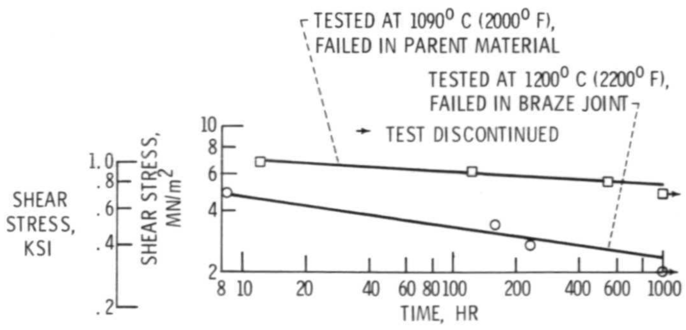


Figure 20. - Creep-rupture shear strength of TD-6 brazed lap joints (4t overlap) in 1.6 mm (0.060 IN.) THICK TD-NiCr (ref. 13).