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by

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PROCESS FOR IMPROVING THE LOW TEMPERATURE DUCTILITY OF TUNGSTEN-BASE COMPOSITES

by

Eugene G. Zukas

ABSTRACT

At temperatures below about 100°C, liquid-phase-sintered tungsten-base composites fail in a brittle manner because of the formation of cleavage cracks in the tungsten spheroids. Improving the ductility, then, would require some alloying addition or treatment which would improve the ductility of these spheroids, or some method of changing the stress distribution, such as putting the surface in compression, which would reduce stress concentrations and thereby require a higher load to initiate fracture.

The ductilizing process used here consists of coating the composite with a ductile metal followed by heat treating at a high enough temperature to insure sufficient diffusion so that the coat and base become integral. The ductile coat is now the 'piece' surface, and the initiation of cleavage cracks requires much greater stresses. Coats of copper, nickel, gold, and cobalt have been used successfully.

A possible added advantage is that the surface properties can now be controlled if certain reflective properties or corrosion resistance are needed. Also soldering or low temperature brazing operations are feasible, allowing the construction or assembly of intricate shapes which could not be accomplished previously.

I. INTRODUCTION

For certain specialized applications, such as penetration projectiles against bunkers and tanks, materials of high density having reasonable strength and some ductility are required. Cost and availability of suitable materials, such as platinum, gold, rhenium, and tungsten-rhenium alloys, prohibit their use except for a few very specialized applications. However, several manufacturers produce tungsten-base composites commercially for this purpose. Such composites fail in a brittle

manner at ambient temperature and below, thereby reducing their reliability for field use. The addition of one or more alloying elements has been tried in an attempt to improve the low temperature ductility of such composites, but with limited success.

This report describes a coating and heat-treating procedure which promotes low temperature ductility in such composites. This should not only improve the reliability of composite components now in use, but should extend the range of successful application.

II. BACKGROUND

Tungsten-base composites contain from 80% to 97% tungsten, with the remainder being generally nickel and copper or iron. Numerous additions or substitutions have been tried, but these generally do not change the alloy characteristics. The elemental powders are mixed and sintered at temperatures from 1673 to 1773K (1400 to 1500°C) which is sufficient to produce a liquid phase, thereby enabling one to produce large parts (100 pounds or so) of essentially theoretical density. This is in contrast to pure tungsten (melting temperature of 3683K, 3410°C) where present-day equipment is incapable of producing large parts having densities approaching theoretical.

The sintered structure of the tungsten-base composites consists of body-centered-cubic tungsten single-crystal spheroids embedded in a face-centered-cubic tungsten-nickel-iron matrix.¹ Face-centered-cubic metals and alloys exhibit ductile behavior to very low temperatures. Thus, the brittle behavior of these composites at temperatures around ambient and below must be due to the single-crystal tungsten spheroids. An earlier study² shows that this is the case, and that such failure is caused by cleavage fracture (brittle failure) of these spheroids.

A number of different alloying elements have been added to liquid-phase-sintered tungsten-base composites in an attempt to improve low temperature ductility.³⁻⁶ Rhenium is the most popular addition since it is reported to lower the ductile-brittle transition temperature in pure tungsten, and in general, promotes low temperature ductility in tungsten.⁷⁻¹⁴ A number of investigators have studied the effects of impurities and methods for their removal because they exert a strong influence on the low temperature behavior of tungsten.¹⁵⁻¹⁷ However, the results of such studies are probably of limited value because impurities generally concentrate in grain boundaries and hence should not have any effect on the behavior of

the tungsten spheroids found in these composites. Studies of the cleavage behavior of tungsten single crystals¹⁸⁻²³ present several experimental facts which must be considered. First, the crystallographic orientation of the single crystals with respect to the applied shear stress is very important. The [100] crystals have the lowest strain to fracture, but with imperfection-free surfaces, even crystals of this orientation can be strained to more than 5% at -196°C. The tensile strengths and yield strengths are similarly orientation dependent. For example, the 0.2% offset yield for the [100] orientation is approximately 345MPa (50,000 psi) at room temperature, whereas it is about 758 to 828 MPa (110-120,000 psi) for the [110] and [111] orientations. Lowering the test temperature to 77K (-196°C) increases these yield strengths. Surface preparation necessary for obtaining low temperature ductility in tungsten single crystals consists of polishing through 4/0 grit emery paper, followed by removal by electro-polishing of an additional minimum of 0.076 mm (0.003 in.) in order to completely remove machining marks, sanding scratches, and other surface imperfections. Crystals of the [100] crystallographic orientation work harden at a much higher rate than do crystals of the other orientations. During low temperature testing, Beardmore and Hull¹⁸ found that grip constraints and superficial defects resulted in cleavage fracture (brittle failure) in crystals close to the [100] orientation. They attributed this to the rapid work-hardening during straining for this crystallographic orientation, pretty much in agreement with the ideas of Seigle and Dickinson.¹⁹ Perhaps this explains the often observed experimental results where single-crystal rods of tungsten can be bent 90° and even more in one direction, but if the bending is stopped at some smaller angle, such as 45°, the crystal can not be straightened, but will break in a brittle manner.

The experimental results discussed above indicate that crystallographic orientation, impurity

content, and surface roughness are all important in achieving low temperature ductility. Diffusion bonding a ductile surface coating to the composite should lessen the effects of surface imperfections, spread the shear stresses over a larger area, and oppose the initiation and opening up of cleavage cracks. In this way, plating with a ductile coat followed by a heat treatment designed to control diffusion bonding of the coat and composite should improve the low temperature ductility of liquid-phase-sintered tungsten-base composites.

III. EXPERIMENTAL TECHNIQUES

The basic composite composition of 95%W-3.5%Ni-1.5%Fe* was chosen since it had been used for a number of other applications. Two series of compositions were studied, one where part of the tungsten was replaced by the same weight percent of rhenium, and the other where part of the tungsten was replaced by the same weight percent of platinum. The replacement additions were in amounts of 1/4%, 1/2%, 3/4%, 1%, 2%, and 4%.

The nickel-iron-rhenium/platinum powders were preblended, and then blended with tungsten powder for an additional 8 hours. This mixture was then isostatically pressed at 345 MPa (50,000 psi) into green compacts about 5 cm diameter by 7.5 cm long (2 in. x 3 in.). These compacts were heated slowly in hydrogen to 1623K (1350°C), held for 2 hours, and then raised to the sintering temperature (1773K, 1500°C). After sintering for 2 hours, they were cooled to 1473K (1200°C), held for 2 hours in vacuum and then furnace-cooled to room temperature.

Oversize blanks for bend specimens were cut from the sintered compacts with a milling cutter. These were then surface-ground to 1.52 x 12.7 x 38.1 mm (0.060 in. x 0.5 in. x 1.5 in.) bend specimens. The bend specimens were then hand-sanded

at right angles to the grinding direction on 180 grit paper until all grinding marks were removed, and then further polished through 600 grit paper with the final grinding direction lengthwise to remove all stress raisers that might cause premature fracture in the bend test. A series of tests were made on specimens at this stage of preparation, not only to determine the effect of rhenium or platinum additions, but also as a base for comparison to the ductility results after the coating and heat-treating operations.

The four different coatings applied were copper, gold, cobalt, and nickel. Nickel and cobalt alloy readily with tungsten, so these were electroplated directly on the composite specimens. Copper and gold are insoluble in tungsten and therefore require a strike coat to promote metallurgical bonding. Thus, for copper and gold coats, a strike layer of cobalt about 0.0025 to 0.0058 mm (0.0001 in. to 0.0002 in) was electroplated onto the surface, followed by electroplating the desired final coat. Coating thicknesses of approximately 0.05 mm (0.002 in) were used. The coated specimens were then held in vacuum at a number of different temperatures up to 1223K (950°C) in order to promote diffusion of the coat with the base composite. A number of holding temperatures were used, because this was one of the experimental parameters. After a 1 hour hold at temperature, the specimens were allowed to cool in vacuum. Because diffusion distance is a function of $t^{1/2}$ (where t is time) and an exponential function of temperature, then for a given bond zone width, small variations in time are insignificant, but temperature must be closely controlled.

A standard bend-test was used²⁴ for ease in comparison of these results with some of our earlier results, as well as literature values from studies on other refractory metals and alloys by other experimentalists. This test is simply the bending of a strip specimen between two supporting rolls by a ram having a radius related to the

*Compositions are in weight percent.

specimen thickness, the ram being lowered at a controlled rate (25.4 mm or 1 in. per minute used here) until fracture. This test is depicted schematically in Figure 1. All specimens that pass through the die without fracturing are ductile but not of equal ductility, so if one wants to inter-compare these materials, then a more severe test is required. The test can be made more severe by reducing the radius of the ram or by increasing the rate of ram travel. Lowering the temperature also decreases ductility, but this is generally a test parameter. Furthermore, the mode of fracture might change with the change in temperature, thereby making comparison invalid. For tests at low temperatures, the bend-test die with the specimen in position was immersed in alcohol, and dry ice added until the bath reached the desired temperature. To insure that the specimens were at the test temperature, they were held in a controlled temperature bath

prior to transfer into the test die, but the small mass of a specimen probably makes the use of such a bath superfluous. Tests were made on an Instron testing machine, and plots of load versus ram travel were obtained for each test. Yield loads could be measured for many of the specimens. Maximum loads were determined for all specimens tested, but these values were considered unreliable, since an unknown friction force is included in this measurement.

Bend tests were generally done at 298, 263, 233 and 193K (25°C, -10°C, -40°C, and -80°C), as well as at a few temperatures to 473K (200°C). Since the program was aimed at improving low temperature ductility, the tests at elevated temperatures were run simply for comparison purposes. The results for all tests are listed in the Appendix.

Fig. 1. Schematic representation of the bend test.

IV. EXPERIMENTAL RESULTS

The effect of rhenium on the room temperature ductility as determined by the bend test is shown in Figure 2. In this plot, all coating metals are combined and treated as if they imparted equal ductility to the composite. The bend-ductility angle decreased inversely with Re content from 14° with no rhenium to 8° for 4% rhenium. Such composites were much too brittle for most uses. However, when coated and heat-treated, the specimens containing either zero or 1/4%Re went through the test die without fracture. The ductility of the coated and heat-treated specimens decreased with increasing rhenium content and specimens containing 4%Re had a bend angle of only about 32° . Lowering the test temperature decreased the ductility, but tests of the coated plus heat-treated composites showed that they were still more ductile at 233K (-40°C) than the uncoated composites were at room temperature. A companion plot is shown in Figure 3, where a small weight fraction of the tungsten was replaced by platinum instead of rhenium. The bend ductility of the uncoated specimens tested at room tempera-

Fig. 2. Improvement in bend ductility for 3.5% Ni-1.5%Fe-(0 to 4)%Re-balance W composites as a result of a ductile metal coating plus a diffusion heat treatment, and the effect of lower test temperatures on this ductility. Note that all coating metals are combined for each test temperature as if they imparted equal ductility.

Fig. 3. Same as Fig. 2 except that platinum is used in place of rhenium.

ture decreased with increasing platinum content from 14° for specimens without platinum to 2° for specimens containing 4% platinum. Similar specimens containing up to 1% Pt went through the die without fracture when they were coated with a ductile metal and heat-treated. Ductility dropped rapidly for the composites containing more than 1%Pt, and even the coated specimens containing 4% platinum were brittle. Lowering the test temperature lowered the bend ductility in much the same manner as for the rhenium alloys.

The heat-treatment temperature for the coated composites is important because adequate diffusion is required to form an integral bond. Yet not enough diffusion should be allowed to either cause an embrittling effect because of alloying or for the exterior portion of the coat to itself become brittle. Since diffusion rate is related to temperature by an exponential function, small temperature differences cause large rate changes. On the other hand, the diffusion rate is proportional to the square root of time, so small time differences will not affect the diffusion distance very much. However, the diffusion rates for different metal coatings on different base composites will be different even when the same time and temperature are used.

Figure 4 shows the effect of heat-treating temperature on bend ductility for copper coatings on 94.75%W-3.5%Ni-1.5%Fe-0.25%Re, for gold on 94.25%W-3.5%Ni-1.5%Fe-0.75%Re, and for nickel on 93%W-3.5%Ni-1.5%Fe-2.0%Pt. For a 1 hour hold at heat-treating temperatures up to at least 473K (200°C), the coat does not become integral with the base composite, and behaves merely as an envelope surrounding the specimen. This does not change the characteristics of the composite surface, and there is no improvement in bend ductility. For copper coatings on the 0.25%Re composite, bend ductility is very much improved by heat-treating temperatures above 773K (500°C) up to almost 1223K (950°C) where most of the coating has diffused into the base composite and bend ductility begins to decrease again. For gold on the 0.75%Re composite, the bend ductility maximum occurs at a heat-treating temperature of 923K (650°C). The 2% Pt composite with a nickel coat never attains a high degree of ductility, but there seems to be no decrease in ductility with heat-treating temperature at least to 1223K (950°C). These results indicate that a heat-treating temperature of 923K (650°C) is a good compromise for studies designed to find the effect of other metals and alloys which can be used for coatings, and the effect of plating thicknesses and other variables.

Fig. 4. Effect of heat-treating temperature on bend ductility for copper, gold and nickel coats on composite bases.

A number of commercial composites were studied² and of those investigated, the W-2 composite⁶ showed the best low temperature ductility. Figure 5 compares the 95%W-3.5%Ni-1.5%Fe composite in both the uncoated and coated plus heat-treated condition with the W-2 composite and one of the P.R. Mallory Company composites. The room temperature ductility of our uncoated composite was considerably below that of either of the commercial composites. However, after copper-coating followed by heat treatment, our composite was much more ductile than either commercial composite. If one specified that a bend-ductility angle of 40° was adequate for a specific use, then the Gyromet 1100 composite would be limited to temperatures above about 333K (60°C), the W-2 composite above about 273K (0°C), but the ductilized composite could be used at temperatures down to almost 193K (-80°C). This improved low temperature ductility should extend considerably the useful applications of the composites.

Kennametal Inc., Latrobe, Pennsylvania.

Fig. 5. A comparison of the bend ductilities of the uncoated and coated plus heat-treated 95%W-3.5%Ni-1.5%Fe composites with commercial composites.

A few experiments were done on copper-coating and heat-treating rolled commercial tungsten sheet. Specimens were cut from 0.76-mm (0.030 in) sheet, the surfaces cleaned on 600 grit paper, a flash coat of cobalt applied followed by a 0.051-mm (0.002-in.) copper coat, and the specimens then heat-treated at either 923, 1073, or 1223K (650°C, 800°C, or 950°C). The coated specimens heat-treated at 923K (650°C) showed much higher ductility at the lower temperatures, but the ductility decreased as the heat-treating temperature was increased, presumably because of an embrittling effect due to alloying of the cobalt with the tungsten and the impurity effect of the copper. These results are shown graphically in Figure 6.

The effect of heat-treating temperature on the bend ductility for a copper coat on a 94.75%W-3.5%Ni-1.5%Fe-0.25%Re composite is shown in Figure 7. Heat-treating at low temperatures (~473K, 200°C) does not result in sufficient diffusion for the coat and base to become an integral unit and, as a consequence, there is no improvement in ductility. At 1223K (950°C) where diffusion is rapid, the copper coat has diffused enough

Fig. 6. The ductilizing effect of a copper coat heat-treated at different temperatures on the low temperature ductility of commercial rolled 0.76 mm (0.030 in) tungsten sheet.

in the 1 hour heat treatment that the exterior surface of the coat has lost some of its original ductility, and the bend ductility of the coated composite has decreased. A similar series of results are shown in Figure 8 for the 94%W-3.5%Ni-1.5%Fe-1.0%Pt composite plated with gold and heat-treated for 1 hour. In this case, the choice of heat-treating temperature is much more critical, but perhaps some of this effect is a result of the base composite being much more brittle in the uncoated condition than were those composites containing less platinum. For most applications, the lowest temperature at which the composite has some degree of ductility is of much greater importance. Figure 9 shows the effect of test temperature on the bend ductility of a 95%W-3.5%Ni-1.5%Fe composite coated with copper and heat-treated at 923K (650°C) for 1 hour. At 233K (-40°C), the bend-ductility angle was 129°, showing that such coated composites exhibit considerable ductility before fracture at temperatures considerably below this (Figure 9). Similar results are shown in Figure 10 for the 94.75%W-3.5%Ni-1.5%Fe-0.25%Re composite coated with copper and heat-treated for 1 hour at 923K (650°C). These results indicate that rhenium additions have an embrittling effect at the lower test temperatures, even in the case of specimens which are given a ductilizing treatment.

Both heat-treating temperatures and test temperatures were varied for the 94.25%W-3.5%Ni-1.5%Fe-0.75%Re composite coated with gold. The results, shown in Figure 11, again indicate that even though the ductilizing process increases the low temperature ductility, brittle base materials cannot be made as ductile as those which have some ductility initially. The additional rhenium again appears to decrease low temperature ductility.

Figure 12 shows that cobalt and nickel coatings on the 94.50%W-3.5%Ni-1.5%Fe-0.50%Pt composite are also very effective in promoting low temperature ductility.

Fig. 7. Effect of heat-treating temperature on the bend ductility of a 94.75%W-3.5%Ni-1.5%Fe-0.25%Re composite coated with copper. 1) Uncoated, B.D. -13° , 2) 473K (200°C), B.D. -13° , 3) 773K (500°C), B.D. $> 180^{\circ}$, 4) 923K (650°C), B.D. $> 180^{\circ}$, 5) 1073K (800°C), B.D. $> 180^{\circ}$, and 6) 1223K (950°C), B.D. $= 91^{\circ}$.

Fig. 8. Effect of heat-treating temperature on the bend ductility of a 94%W-3.5%Ni-1.5%Fe-1.0%Pt composite coated with gold. 1) Uncoated, B.D. -13° , 2) 473K (200°C), B.D. -14° , 3) 773K (500°C), B.D. -141° , 4) 923K (650°C), B.D. $> 180^{\circ}$, and 5) 1023K (800°C), B.D. -66° .

Fig. 9. Effect of test temperature on the bend ductility of a 95%W-3.5%Ni-1.5%Fe composite coated with copper. 1) Uncoated at 298K (25°C), B.D. 14°; 2) 298K (25°C), B.D. >180°; 3) 263K (-10°C), B.D. >180°; 4) 233K (-40°C), B.D. 129°; and 5) 193K (-80°C), B.D. 23°.

Fig. 10. Effect of test temperature on the bend ductility of a 94.5%W-3.5%Ni-1.5%Fe-0.25%Re composite coated with copper. 1) Uncoated at 298K (25°C), B.D. 13°; 2) 298K (25°C), B.D. >180°; 3) 263K (-10°C), B.D. 136°; and 4) 233K (-40°C), B.D. 45°.

Fig. 11. The effect of heat-treating temperature and test temperature on the bend ductility of the 94.25% W-3.5%Ni-1.5%Fe-0.75%Re composite coated with gold. 1) Uncoated at 298K (25°C), B.D. = 6°, 2) heat-treated at 473K (200°C) and tested at 298K (25°C), B.D. = 147°, 3) heat-treated at 923K (650°C) and tested at 298K (25°C), B.D. = 144°, 4) heat-treated at 923K (650°C) and tested at 263K (-10°C), B.D. = 23°, and 5) heat-treated at 1073K (800°C) and tested at 233K (-40°C), B.D. = 10°.

Fig. 12. Effect of heat-treating temperature on the room temperature bend ductility of the 94.5%W-3.5% Ni-1.5%Fe-0.5%Pt composite coated with either cobalt or nickel. 1) Uncoated, B.D. = 16°, 2) cobalt coat heat-treated at 923K (650°C), B.D. = >160°, 3) nickel coat heat-treated at 1073K (800°C), B.D. = >180° and 4) nickel coat heat-treated at 1223K (950°C), B.D. = >180°.

V. DISCUSSION

When tungsten-base W-Ni-Fe composites (or similar composites) are liquid-phase-sintered, the resulting structure consists of single-crystal tungsten spheroids embedded in a ductile face-centered-cubic W-Ni-Fe matrix. At high temperatures, these composites fail by a tearing of the matrix. At low temperatures, they fail in a brittle manner by cleavage of the tungsten spheroids. Unfortunately, the transition from ductile fracture to brittle fracture occurs at room temperature, or perhaps just slightly above room temperature. Additions which alloy with tungsten generally make the tungsten even more brittle, except for rhenium which can ductilize tungsten and has been reported to lower its ductile-brittle transition to 273K (0°C) at the magic 75%W-25%Re composition. Rhenium in such large additions does not seem to ductilize the tungsten-base composites, and even if it did, ductility down to only 273K (0°C) would still be unsatisfactory for most applications.

Cleavage fracture of tungsten single crystals is initiated by surface imperfections. For example, polishing scratches from 600 grit emery paper can raise the ductile-brittle transition temperature to ambient and perhaps even higher. Furthermore, in the liquid-phase-sintered composites, junctions of two or more tungsten spheroids are numerous and such junctions can serve as built-in notches for stress concentration. Many such junctions, by the laws of probability, are at or very near the specimen surface. These junctions which would serve as stress concentration points would not be made ineffective by alloying additions or by impurity removal. Thus, possible solutions are to find ways to decrease their influence either by 1) distributing the stress uniformly so that they are no longer stress concentrators, or by 2) displacing them from the surface so that fracture is no longer initiated by them. These goals have been accomplished by coating the composite surfaces with a ductile material and heat-treating for the proper time at

the right temperature to make this coating an integral part of the piece.

Coatings of copper, gold, cobalt and nickel have been deposited and diffusion-bonded by heat treating operations. As the results show, heat treatments at 473K (200°C) for 1 hour simply anneal and soften the deposited coat without sufficient diffusion taking place for the coat and composite to become integral. Such a coat is merely an envelope surrounding the base composite and does not improve the low temperature ductility. Heat-treating where diffusion does take place now makes the coating serve as the piece surface and requires fracture to initiate in the ductile coat rather than at spheroid junctions or at surface scratches. This tends to keep the composite surface in compression, and distributes the stress more uniformly, thereby greatly improving ductility. Copper and gold are essentially insoluble in tungsten, and to use these metals effectively as ductilizing coats, a flash or strike coat of a metal such as cobalt or nickel, which is soluble in tungsten, is required. There appears to be no reason why other ductile metal or alloy coats would not be satisfactory, as for example platinum, rhenium, tantalum, or others, as long as they can be made an integral part of the base composite and are themselves ductile at low temperature.

VI. OTHER COATING ADVANTAGES

Coating allows a wide latitude in controlling surface properties. For example, if the anticipated environment would chemically react with the composite, a coating resistant to such attack could be chosen. In other cases, surface finish or reflectivity might be important for some specialized use, and these properties could be readily controlled by choosing the proper coating material.

Assembly of parts would be made easier. For example, parts coated with copper could be soft-soldered, or brazed with a low melting brazing alloy. Satisfactory joints could be readily

made, vacuum-tight if necessary, without decreasing ductility appreciably since such joining processes do not require temperatures higher than about 1073K (800°C). Also, surface flaws in a composite could be repaired in much the same way by soldering in plugs or by simply filling the pore or flaw with some other satisfactory material. Perhaps the soldering or brazing of rings, fins, or other protuberances onto composites rather than having them machined-in so that they are integral would make the use of smaller sintered compacts possible, thereby reducing overall material requirements and machining costs.

VII. CONCLUSIONS

Liquid-phase-sintered tungsten-base composites have been given an integral coating of copper, gold, cobalt, or nickel. Such coatings reduce the tendency for cleavage fracture, thereby making the coated composites much more ductile at the lower temperatures.

Such coatings could be beneficial in other ways, such as for corrosion resistance, in applications where special surface properties are required, and to allow soldering or brazing to be done, thereby making joining operations feasible.

The substitution of other coating materials should be possible, thereby extending the uses for such unusual composite materials.

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APPENDIX

EFFECT OF COATING METAL AND HEAT TREATMENT ON BEND DUCTILITY

Experimental Test Data

Composition	Coat	Heat-Treat Temperature °C K	Test Temperature °C K	Bend Ductility Angle Degrees
95%W-3.5%Ni-1.5%Fe	none	-- --	25 298	14
	copper	850 923	25 298	>180
	"	850 923	-10 263	>180
	"	850 923	-40 233	129
94.75%W-3.5%Ni-1.5%Fe-0.25%Re	none	-- --	25 298	13
	Copper	200 473	25 298	13
	"	500 773	25 298	>180
	none	500 773	25 298	4
94.5%W-3.5%Ni-1.5%Fe-0.5%Re	copper	850 923	25 298	>180
	none	850 923	25 298	5
	copper	800 1073	25 298	>180
	none	800 1073	25 298	5
	copper	950 1223	25 298	91
	none	950 1223	25 298	5
	copper	650 923	25 298	>180
	"	850 923	-10 263	136
	"	850 923	-40 233	45
	none	-- --	25 298	12
94.25%W-3.5%Ni-1.5%Fe-0.75%Pt	nickel	850 923	25 298	60
	"	850 923	-10 263	102
	"	850 923	-40 233	50
	none	-- --	25 298	6
94.0%W-3.5%Ni-1.5%Fe-1.0%Pt	gold	200 473	25 298	147
	"	850 923	25 298	144
	"	850 923	-10 263	23
	"	800 1073	-40 233	10
94.0%W-3.5%Ni-1.5%Fe-2.0%Pt	none	-- --	25 298	9
	copper	650 923	-10 263	11
	none	-- --	25 298	8
	copper	850 923	25 298	63
93.0%W-3.5%Ni-1.5%Fe-2.0%Pt	"	850 923	-10 263	50
	"	850 923	-40 233	29
	"	850 923	-80 193	16
	none	-- --	25 298	8
91.0%W-3.5%Ni-1.5%Fe-4.0%Pt	gold	500 773	25 298	23
	"	850 923	25 298	32
	"	850 923	-10 263	27
	"	800 1073	25 298	14
94.75%W-3.5%Ni-1.5%Fe-0.25%Pt	none	-- --	25 298	13
	cobalt	850 923	25 298	82
	copper	850 923	-10 263	136
	"	850 923	-40 233	37
94.5%W-3.5%Ni-1.5%Fe-0.50%Pt	"	850 923	-80 193	20
	none	-- --	25 298	16
	nickel	850 923	25 298	>180
	"	850 923	-40 233	48

Experimental Test Data

Composition	Coat	Heat-Treat Temperature °C K	Test Temperature °C K	Bend Ductility Angle Degrees
94.25%W-3.5%Ni-1.5%Fe-0.75%Pt	none	-- --	25 298	12
	copper	850 923	25 298	>180
	"	850 923	-10 263	68
	"	850 923	-40 233	32
94.0%W-3.5%Ni-1.5%Fe-1.0%Pt	"	850 923	-80 193	27
	none	-- --	25 298	13
	gold	200 473	25 298	14
	"	500 773	25 298	141
93.0%W-3.5%Ni-1.5%Fe-2.0%Pt	"	650 923	25 298	>180
	"	800 1073	25 298	66
	none	-- --	25 298	7
	nickel	500 773	25 298	18
91.0%W-3.5%Ni-1.5%Fe-4.0%Pt	"	650 923	25 298	38
	"	650 923	25 298	36
	"	800 1073	25 298	16
	"	950 1223	25 298	50
94.8%W-3.18%Ni-0.77%Fe-1.17%Mn-0.05%Ru	none	-- --	25 298	2
	copper	650 923	25 298	3
	"	650 923	25 298	3
	"	650 923	25 298	2
100%W-Rolled 85% (to 0.030" sheet)	"	650 923	25 298	2
	"	-- --	25 298	2
	"	-- --	25 298	3
	"	-- --	80 333	3
94.0%W-3.18%Ni-0.77%Fe-1.17%Mn-0.05%Ru	"	-- --	100 373	8
	"	-- --	150 423	6
	"	-- --	200 473	10
	"	-- --	200 473	8
94.0%W-3.18%Ni-0.77%Fe-1.17%Mn-0.05%Ru	copper	200 473	25 298	3
	"	500 773	25 298	4
	"	850 923	25 298	16
	"	800 1073	25 298	8
100%W-Rolled 85% (to 0.030" sheet)	"	950 1223	25 298	4
	none	-- --	25 298	10
	"	-- --	100 373	32
	"	-- --	150 423	>180
94.0%W-3.18%Ni-0.77%Fe-1.17%Mn-0.05%Ru	copper	850 923	25 298	>180
	"	850 923	-10 263	>180
	"	450 923	-40 233	34
	"	800 1073	25 298	7
94.0%W-3.18%Ni-0.77%Fe-1.17%Mn-0.05%Ru	"	800 1073	-10 263	16
	"	800 1073	-40 233	6
	"	950 1223	25 298	5
	"	950 1223	-10 263	6