Final Report

Project Title: Development of New Stainless Steel

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Award Number: DE-FG36-03GO13011

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Executive Summary

A new family of innovative martensitic stainless steels, 521-A, 521-B, and 521-C has been developed as high strength fastener (bolt) materials for use at moderate temperatures in turbine engines, including steam turbines, gas turbines, and aircraft engines. The primary objective of the development program was to create a martensitic stainless steel with high strength at moderate temperatures, and which could replace the expensive nickel-based superalloy IN 718 in some fasteners applications. A secondary objective was to replace conventional 12Cr steels such as AISI 422 used as blades, buckets and shafts that operate at intermediate temperatures in turbine engines with stronger steel. Team members include Advanced Steel Technology, LLC (lead), Universal Stainless & Alloy Products, Inc., Honeywell, and General Electric Power Systems. Total Phase 1 cost was \$69,269, while DOE support totaled \$35,000.

The composition of the new alloys was specifically designed to produce excellent mechanical properties while integrating heat treatment steps into production to reduce energy consumption during manufacturing. As a result, energy consumption during production of rolled bar products is estimated to be reduced by 47-65% compared to conventional materials and production costs are lower. Successful commercialization of the new alloys would permit the installed cost of certain turbine engines to be reduced without sacrificing high availability or operational flexibility, thereby enhancing the global competitiveness of U.S. turbine engine manufacturers. Moreover, the domestic specialty steel industry would also benefit through increased productivity and reduced operating costs, while increasing their share of the international market for turbine engine fasteners, blades, buckets and shafts.

Project Description

Project Objective

The primary objective was to create a new family of martensitic stainless steel with very high strength at moderate temperatures which could replace expensive nickel-based superalloys in some fastener (bolt) application used at moderate temperatures in turbine engines. A secondary objective is to replace conventional martensitic stainless steel components which operate at intermediate temperatures in steam turbines and gas turbines with stronger steel. The new steels may also find applications as stainless rebar.

Background

The first step of the development program was a comprehensive literature search and formulation the of three experimental heat chemistries. The composition of each new steel was specifically designed to be strengthened by precipitation hardening, solid solution strengthening, ultra-fine grains, and a fine dispersion of coarsening-resistant MX particles.

The original development strategy was to (i) make several very small heats (~2 lb. “button” ingots), (ii) heat treat the button ingots, (iii) analyze the microstructure of the button heats, (iv) melt one small commercial-size heat (10,000 lb. ingot), and (v) apply the desired thermal mechanical treatment to the ingot. Because the button heats were so small, however, it would not have been possible to apply the desired thermal mechanical treatment to them. As such, it was decided to alter the original development strategy and make three medium-size heats (~50 lb. ingots) in lieu of several button heats and one commercial ingot. The desired thermal mechanical treatment would be applied to the medium-size ingots instead of just one large ingot.

Unlike the button ingots, the medium-sized ingots would be large enough to apply the desired thermal mechanical treatment and learn if the combination of ingot chemistry and thermal mechanical processing would produce the desired results. Because of the altered development approach, more information was obtained by making several medium-size ingots rather than one large ingot. The results from the medium ingots were used to identify the optimal chemistry that offered the best combination of hot workability, high strength, and good toughness.

The nominal compositions of the three new steels (see Table 1) were specifically designed to produce fine grains and excellent mechanical properties by utilizing a novel thermal-mechanical processing method. By doing so, the conventional heat treating steps of austenitizing and quenching are eliminated, thereby reducing energy consumption and processing costs. Based on results from prior work employing similar thermal mechanical treatment and specially-designed steels, it was believed that the novel processing method would result in high yield and ultimate tensile strengths at moderate temperatures.

The three experimental heats were melted by Crucible Research Corp. (Pittsburgh, PA). Each heat was made using induction melting. Initial heat-up was done under vacuum. Alloy additions and subsequent heating were done by backfilling with argon (99.99% pure). The three experimental heats were melted and teemed into 4” square molds. The nominal heat size of each ingot was ~48 lb.

Table 1. Nominal alloy chemistry of three new alloys and conventional materials

Alloy	C	Cr	Ni	Mo	Cu	Al	other
521-A	0.1	11	3	0.5	2		Ti, V, Nb
521-B	0.1	11	7	2		1	Ti, V, Nb
521-C	0.1	11	7	2	3	1	Ti, V, Nb
AISI-422	0.23	12	0.8	1			1W, 0.2V
H-46	0.18	12	0.5	1			0.3 V, 0.5 Nb
17-4PH	0.07 max	17	4		4		0.3 Nb
15-5PH	0.07 max	15	5		3.5		0.3 Nb
718	0.08 max	19	53	3.1		0.5	5.3 Nb, 0.9 Ti
13-8PH	0.05 max	13	8	2.3		1.1	
Custom 455	0.05 max	12	8.5	0.5 max	2		0.3 Nb, 1.1 Ti

All ingots were conditioned by milling the four flat sides of each ingot and grinding the corner edges. By doing so, minor surface imperfections such as scabs, laps, and small tears inherited from the melting and casting operations were removed. The conditioned ingots were then forged into semi-finished round-cornered square (RCS) bars.

The final length of the forged bars was between 25" and 27". No problems were encountered during forging. The net weight of each forged bar was about 31 lb.

Each of the three forged bars was then cut into three smaller bars, each about 9" long and weighing about 10 lb. each. A code was stamped on each of the three smaller forged bars from each heat to indicate the location within the original larger forged bar from where they were cut. Code "II" indicates that the bar was closest to the hot top end of the original ingot, Code "I" indicates that the forged bar was cut from the middle of the ingot, and the absence of a code indicates that bar was located closest to the bottom of the original ingot.

The experimental forged RCS bars were rolled into round bars and given one of several thermal mechanical treatments. Specimens were then machined and initial properties were determined.

Rolling

Two RCS bars each of 521-A, 521-B, and 521-C were rolled at Braeburn Alloy Steel. In each case the starting bar size was approximately 2.25" RCS and the final size was 0.625" round bar. Before rolling all bars were fully conditioned (surface ground) to remove minor defects. Fifteen rolling passes were used to form the final bar shape and size. One of the two bars from each composition was allowed to air cool to room temperature after rolling, while the other bar was air cooled to an intermediate temperature before being placed in a furnace and isothermally held before being air cooled to room temperature. The later series of bars, which were given an isothermal hold, were denoted as A1, B1, and C1, whereas the bars that were air cooled to room temperature after rolling are denoted simply as A, B, and C. After rolling all bars were cut into 16" section lengths for ease of handling.

Heat treatment

Bars from each composition were either austenitized at 1700°F and air cooled, or not austenitized at all. Aging of the initial series of bars was performed for four hours at either 925°F or 975°F. Therefore, there were a total of four heat treatments. (Subsequent aging of bars was done at 1025°F and will be discussed later.)

Initial mechanical properties

Given the number of chemistries (3), thermal mechanical treatments (2), and heat treatment combinations (4) a total of 18 different alloy/TMT combinations were investigated initially. A unique identifying number between 1 and 18 was assigned to

each alloy/TMT combination. See Table 2. The ID number was used to characterize the mechanical properties of the various alloy/TMT combinations.

Table 2. Key to different alloy/TMT combinations

Austenitizing temperature	none	none	1700°F	1700°F
Age temperature	925°F	975°F	925°F	975°F
Alloy 521A	7	8	1	2
Alloy 521B	9	10	3	4
Alloy 521C	11	12	5	6
Alloy 521 A1	13	14	--	--
Alloy 521 B1	15	16	--	--
Alloy 521 C1	17	18	--	--

After heat treating the bars room temperature toughness and hardness values were determined. Results for the 18 unique alloy/TMT combinations are given in Figure 1.

All variants of Alloy 521-A (1, 2, 7, 8, 13, and 14) exhibited hardness values between 35 and 41 Rc, and reasonable impact toughness, varying between 20 and 86 ft.-lb. As expected in all cases tempering at 975°F (Nos. 2, 8, and 14) produced lower hardness and higher toughness compared to the samples that were tempered at 925°F. It was also observed that austenitizing Alloy 521-A at 1700°F prior to aging did not lead to any noticeable improvement in overall mechanical properties compared to aging (only) the bars directly after rolling.

In all cases involving Alloys 521-B and 521-C, hardnesses were high (47-51 Rc), but room temperature impact toughness values were low (< 7 ft.-lb.) Room temperature toughness levels that are less than 10 ft.-lb. are unacceptable. As such, it was decided to re-age the bars at 1025°F to try to increase their toughness without decreasing the hardness values too dramatically.

The mechanical properties (*i.e.* yield and tensile strength, impact toughness) of the three experimental heats, (521-A, 521-B, and 521-C) were also determined. Results are given in Table 3.

Figure 1. Hardness and toughness of 18 different variants of 521 alloys and thermal mechanical processing.

Mechanical properties

Three heat treatments were applied to each grade: as given in Table 3, “N+T” indicates that the alloy was normalized (air cooled) from an austenitizing temperature of 1700°F, and tempered (or aged); “T” indicates that the alloy was tempered (aged) only; and “ISO-T” indicates that the alloy was given an isothermal hold immediately after rolling, air cooled to room temperature, then tempered (aged). Tempering occurred at 925°F or 975°F for all bars. In some cases when the room temperature toughness after tempering was unacceptably low (*i.e.* < 10 ft.-lb.), the steel bars which had been tempered at 925°F or 975°F were retempered at 1025°F in an attempt to increase the toughness. In these cases, an extra “T” appears in the heat treat designation in Table 3.

The data indicate that for 521-A, the yield strength ranged from 146 ksi. to 175 ksi., while the toughness ranged from 23 ft.-lb. to 78 ft.-lb. The data suggest that by simply tempering the alloy after rolling (*i.e.* no austenitizing and quenching), the best combination of strength and toughness were attained. For example, by tempering at 925°F, the alloy exhibited high strength (175 ksi.) and reasonable room temperature Charpy impact toughness (33 ft.-lb.). Tempering at 975°F produced a slightly lower yield strength (171 ksi.) and slightly greater toughness (42 ft.-lb.). The trade off between strength and toughness is expected. The properties of the tempered-only heat treatments for 521-A are highlighted in bold in Table 3.

The effect of heat treatment on mechanical properties (ultimate tensile strength and toughness) is shown graphically for alloy 521-A in Figure 2. Note that quenching and tempering resulted in relatively low strength and only modest toughness, whereas in the tempering-only case, higher strength and comparable toughness resulted. When the alloy was held isothermally at an intermediate temperature, cooled to room temperature, then tempered, impact toughness was greatest, but strength was not as great as that of the tempered-only case.

Table 3. Mechanical properties of experimental heats (properties in red are suspect)

Alloy	Heat treat	Aging temp. (°F)	YS (ksi.)	UTS (ksi.)	Elong. (%)	RA (%)	Hardness (Rc)	CVN (ft.-lb.)
521-A	N+T	925	150	161	19	66	36.7	23
	T		175	189	19	63	41.3	33
	ISO-T		161	165	18	66	37.5	54
	N+T	975	146	155	20	68	35.7	55
	T		171	178	20	63	40.2	42
	ISO-T		155	158	19	67	36.0	78
521-B	N+T	925	216	232	13	43	47.2	2
	T		230	249	13	54	49.2	3
	ISO-T		236	244	13	51	49.4	3
	N+T	975	220	232	13	51	46.2	3
	T		236	250	12	54	48.4	4
	ISO-T		236	243	12	50	48.3	5
	N+TT	925,1025	205	211	19	59	43.6	8
	TT		222	229	13	57	47.7	12
	ISO-TT		215	220	12	54	47.2	16
	N+TT	975,1075	200	206	19	61	44.7	8
	TT		87	224	13	58	47.2	18
	ISO-TT		213	216	19	56	45.6	16
521-C	N+T	925	238	257	6	17	49.8	3
	T		207				52.1	3
	ISO-T		243	251	12	50	49.9	7
	N+T	975	234	247	11	46	48.4	3
	T		233	250	18	51	49.8	7
	ISO-T						49.9	5
	N+TT	925,1025	206	213	14	56	45.0	8
	TT		213	222	13	54	46.8	21
	ISO-TT		214	220	12	53	46.5	16
	N+TT	975,1075	211	219	12	53	46.5	16
	TT		210	219	14	56	46.3	24
	ISO-TT		213	219	12	55	46.0	20

The yield and ultimate tensile strengths of alloys 521-B and 521-C are significantly higher than those of the alloy 521-A, due to the higher amounts of molybdenum and nickel, among other elements, in 521-B and 521-C. However, toughness of 521-B and 521-C when tempered at either 925°F or 975°F was low (< 10 ft.-lb.) in all cases. Toughness increased somewhat by retempering at 1025°F with concomitant decrease in strength. Nonetheless, the highest toughness attained for 521-B was 18 ft.-lb. in

which the UTS was 224ksi., and for 521-C was 24 ft.-lb., in which the yield strength was 210 ksi. and the UTS, 219 ksi.

The effect of heat treatment on toughness and UTS for alloys 521-B and 521-C is shown in Figures 3 and 4, respectively.

Figure 2. Effect of heat treatment on room temperature toughness vs. UTS for 521-A.

In general the temper-only heat treatment produced the best combination of strength and toughness for 521-B and 521-C (as with 521-A), as indicated in Figures 3 and 4. The highest ultimate tensile strength attained with 521-B was about 249 ksi., however, the toughness was low (4 ft.-lb.). The highest UTS with reasonable toughness (12 ft.-lb.) was 228 ksi. and was obtained when 521-B was in the tempered-only heat treatment condition.

For alloy 521-C the highest UTS attained was 257 ksi., but, again, in this condition it exhibited low toughness (3 ft.-lb.). An ultimate tensile strength of 222 ksi. was attained with reasonable toughness of 21 ft.-lb. and occurred with a tempered-only heat treatment.

Figure 3. Effect of heat treatment on room temperature toughness vs. UTS for 521-B.

Figure 4. Effect of heat treatment on room temperature toughness vs. UTS for 521-C.

As the data suggest, the properties of alloy 521-A compare favorably with those of conventional 12Cr steels such as AISI-422, H-46, as well as the precipitation hardening steels, 17-4PH and 15-5PH. In all cases, 521-A offers greater strength and greater (or comparable) toughness. Compared to the nickel-based superalloy, IN 718, alloy 521-A exhibits greater yield strength and only slightly lower toughness - but at substantial cost savings since 521-A is iron-based, not nickel-based. With the exception of AISI-422 and H-46 (both of which contain lower amounts of nickel than does 521-A, but higher levels of molybdenum) the raw material cost of alloy 521-A is lower than that of all other alloys listed in Table 4. See Table 1 for compositions of the alloys listed in Table 4. An alloy's raw material cost scales with the level of nickel, molybdenum, chromium and copper in it's composition.

Table 4. Mechanical property comparison of 521 alloys versus conventional steels

Alloy	YS (ksi.)	UTS (ksi.)	Elong. (%)	RT CVN (ft.-lb.)	Rc	Data source
521-A	175	189	19	33	41.1	WMTR, USAP
AISI 422	125	149	13	15		Alloy Digest
H-46	117	141	18	16		USAP
17-4PH (H1025)	162	168	16	40	38	CarTech
15-5PH (H925)	175	190	14	25	42	CarTech
718	160	200	25	45		Allvac
521-B	222	229	13	12	47.3	WMTR, USAP
521-C	210	219	14	24	46.5	WMTR, USAP
13-8PH (H950)	210	225	12	20	47	CarTech
Custom 455 (H950)	225	235	12	14	48	CarTech

The best mechanical properties of alloys 521-B and 521-C are comparable to those of conventional high strength precipitation hardening steels, 13-8PH and Custom 455 as indicated in Table 4. Because the mechanical properties are not significantly superior (with the cost being comparable) to that of the existing alloys, however, 521-B and 521-C offer no clear advantage other than a streamlined heat treatment (e.g., tempered only) compared to the other conventional steels of comparable strength.

In the final phase of testing, elevated temperature tensile properties for 521-A (tempered at 925°F) were determined at 600, 700, 800, 900, and 1000°F. Results for the yield strength and ultimate tensile strength are shown in Figures 5 and 6 with data from conventional materials, 15-5PH and nickel based IN718 included for comparison. Given the lower amounts of nickel, chromium, copper and niobium in 521-A versus 15-5PH, and the fact that 521-A would not need to be austenitized and quenched (only tempered after rolling), it was estimated that the cost to produce 521-A rolled bar would be about \$0.27/lb. less than 15-5PH, given the same melting technique. Note in Figures 5 and 6 that 521-A exhibits higher strengths (yield and ultimate tensile) than that of 15-5PH at all elevated temperatures investigated. Data for IN 718 is also given for reference, but 521-A is not designed to replace IN 718.

Elevated temperature tensile properties for 521-B (1025°F temper) were also determined at 600, 700, 800, 900, and 1000°F and are shown in Figures 7 and 8. Data

from 13-8PH and IN 718 are given for reference. Note that the strength of 521-B is greater than that of 13-8PH at all elevated temperatures investigated and its yield strength and ultimate tensile strength is greater than that of IN 718 at temperatures up to about 850 and 700°F, respectively. Given these properties and the dramatically reduced cost versus IN 718, 521-B may be able to replace IN 718 in certain applications.

Figure 5. Effect of temperature on yield strength of 521-A, 15-5PH, and IN 718

The tensile properties of alloy 521-A in the as-rolled condition were also determined to investigate the possibility of using 521-A as stainless steel rebar. Results are given in Table 5. The results given in Table 5 are very encouraging and indicate that 521-A may have applications as stainless steel rebar in certain environments.

Table 5. As-rolled mechanical properties of 521-A (given isothermal hold during rolling)

0.2% yield strength	Ultimate tensile strength	Elongation*	RA	Modulus
132.7 ksi.	160.6 ksi.	23.07%	65%	28.1 Msi.

* in 4 inch gauge section

Figure 6. Effect of temperature on the UTS of 521-A, 15-5PH, and IN718.

Figure 7. Effect of temperature on yield strength of 521-B, 13-8PH, and IN718

Figure 8 Effect of temperature on the UTS of 521-B, 13-8PH, and IN718

Metallography

Optical metallography was performed on 521-A and 521-B. In general both alloys exhibited very fine grain size as seen in Figures 9-13, in which both transverse and longitudinal orientations are shown. Also evident in Figures 9-13 are very small precipitates, which appear as tiny black dots. These particles most likely are MX precipitates and add to the strength of the alloys, both at room temperature and elevated temperatures.

Alloy 521-B did show signs of centerline segregation, but alloy 521-A did not (due to its lower alloy content vs. 521-B). As such, in commercial production, alloys 521-B (and 521-C, because its chemistry is similar to that of 521-B) may need to be remelted (vacuum arc remelted or electro slag remelted) after initial air melting in order to minimize or eliminate centerline segregation.

Figure 9. 521-A (H925) longitudinal orientation 500x.

Figure 10. 521-A (H925) transverse orientation 500x.

Figure 11. 521-A (H925) transverse orientation 1000x.

Figure 12. 521-B (H1025) longitudinal orientation 500x.

Figure 13. 521-B (H1025) transverse orientation 1000x.

Patents

None

Publications / Presentations

None

Appendix A. Final Task Schedule

Final Task Schedule

Task Number	Task Description	Task Completion Date				Progress Notes
		Original Planned	Revised Planned	Actual	Percent Complete	
1	Literature review	09/30/03		09/30/03	100%	Completed
2	Design steels	11/30/03	12/31/03	12/31/03	100%	Completed
3	Melt trial steel heats	03/31/04		3/31/04	100%	Completed
4	Roll trial heats; analyze	07/31/04	8/31/04	8/31/04	100%	Completed
5	Test rolled steel samples	12/31/04	3/31/05	3/31/05	100%	Completed
6	Project management	05/31/05		5/31/05	100%	Completed

Appendix B. Final Spending Schedule

Final Spending Schedule

Project Period:

08/01/03 to 05/31/05

Task	Approved Budget	Final Project Expenditures
Task 1 Literature review	\$ 500	\$ 500
Task 2 Design steels	1,269	1,769
Task 3 Melt trial steels heats	8,000	8,000
Task 4 Roll trial heats; analyze	10,000	10,000
Task 5 Test rolled steel samples	12,000	12,000
Task 6 Project management	37,000	36,500
Total	\$ 69,269	\$ 69,269
DOE Share	35,000	35,000
Cost Share	34,269	34,269

Appendix C. Final Cost Share Contributions

Final Cost Share Contributions

Funding Source	Approved Cost Share		Final Contributions	
	Cash	In-Kind	Cash	In-Kind
Advanced Steel Technology, LLC		\$ 21,269		\$ 21,269
Universal Stainless & Alloy Products, Inc.		10,000		10,000
General Electric		500		500
Honeywell		2,500		2,500
Total		\$ 34,269		\$ 34,269
Cumulative Cost Share Contributions				\$ 34,269

Appendix D. Energy Savings Metrics

Energy Benefits

During the hot rolling and heat treatment of martensitic stainless steels, significant amounts of energy are consumed during the (i) soaking of the ingot or bloom before rolling it to final size, (ii) austenitizing the rolled bar, and (iii) tempering the final product. Most energy is consumed to heat the ingot or bloom to typical hot working temperatures. A large amount of energy is also used to reheat the bar to austenitizing temperatures (1900°-2000°F) and hold for a time that depends on component size, as part of the final heat treatment. A smaller amount of energy is consumed during tempering of the bar, which is done at a relatively low temperature.

Heat treatment of IN 718 consumes greater amounts of energy compared to AISI 422 primarily because of the long intermediate aging treatment (8 hours at 1350°F) and final aging treatment (20 hours at 1200°F) for IN 718 that are not required for AISI 422. Soaking parameters are similar to those of AISI 422.

The heat treatment of the new 521 alloys (A, B, or C) would be significantly different than that of either AISI 422 or IN 718, and would result in considerable energy savings (47% vs. AISI 422 and 65% vs. IN 718). The energy saved is based on the specific amount of energy consumed (BTUs per pound) to soak the bloom prior to rolling, and to austenitize, age, and/or temper the rolled bar after rolling. The specific energy consumption associated with the respective heat treatment steps for AISI 422, IN 718, and alloy 521 is summarized in Table D1. (See the “Metrics Summary” section of this Appendix for more details.) The specific energy required to soak the bloom is independent of material and estimated to consume approximately 282 BTU/lb. Austenitizing AISI 422 accounts for 275 BTU/lb., while tempering requires 242 BTU/lb. Intermediate aging of IN 718 consumes about 386 BTU/lb., while final aging requires an additional 540 BTU/lb.

After hot rolling, alloy 521 (A, B, or C) would be cooled to room temperature and tempered (141 BTU/lb.) for a relatively short time compared to 12Cr steels. As such, the thermal-mechanical processing schedule of 521-A results in a net energy decrease of about 375 BTU/lb. (47% energy savings) compared to the conventional processing of AISI 422, and a decrease of 785 BTU/lb. (65% energy savings) versus the heat treatment utilized for IN 718.

Table D1. Specific energy consumed to roll bar products (BTU / lb.)

Operation	AISI 422	521-A	IN 718
Soaking	282	282	282
Intermediate aging	n/a	n/a	386
Austenitizing	275	n/a	n/a
Tempering or Final aging	242	141	540
TOTAL	798	423	1,208
Energy saved if 521-A were used	47%	--	65%

Economic Benefits

Implementation of the new technology will lead to quality improvements in rolled bar products due to the following reasons:

- Bar warpage and quench cracking are eliminated because water quenching is not used during heat treatment.
- The risk of oil fires and environmental concerns regarding disposal of used quench oil are eliminated because oil quenching is not used.
- Productivity will increase and in-process inventory costs will decrease because austenitizing and quenching steps are eliminated resulting in streamlined production.
- Successful development of 521 alloys would enable U.S. specialty steel companies and turbine engine OEMs to become more competitive in the global marketplace and potentially increase employment as demand for the new product grows.

Markets in which the new steel will compete will be primarily high strength fasteners but will also include buckets, blades and shafts for various turbine engines including land-based gas turbines, aircraft engines, steam turbines, and marine and industrial combustion turbines. The current annual market size for stainless steel fasteners, blades, buckets and shafts is estimated to be \$750 million or 150,000 tons per year. Future projections for market value, market size and estimated market share penetration are given in Table D2.

Table D2. Total market value, size, and estimated market penetration of new technology

Year	Total market value	Market size (tons/yr.)	Market share penetration, est.
2005	\$750 million	150,000	0%
2013	\$1.20 billion	240,000	5%
2023	\$2.10 billion	430,000	10%

Assumptions used in Table D2:

- Average global market growth rate: 6% / year (compounded)
- Weighted average bar price: \$2.50 / lb. (includes stainless steel and nickel-based alloys)

The cost to produce bar stock for fasteners, blades, buckets and shafts includes the material cost and the processing (hot rolling and heat-treating) cost. The estimated manufacturing costs per pound for 521-A, AISI 422 and IN 718 are given in Table D3.

Table D3. Estimated costs (per pound) of AISI 422, IN 718 and 521-A

Alloy	Material cost	Processing cost	Total cost
AISI 422	\$1.25	\$0.75	\$2.00
IN 718	\$6.00	\$1.50	\$7.50
521-A	\$1.35	\$0.50	\$1.85

Assumptions used in Table D3:

- AISI 422 and 521-A are melted in an electric arc furnace and argon oxygen decarborized.
- IN 718 is melted in a vacuum induction furnace.
- All materials are vacuum arc remelted or electro-slag remelted.
- Material cost includes (i) charge cost based on current prices of scrap and alloying elements, (ii) melt electrode and remelt electrode into ingot, (iii) condition ingot, (iv) process (roll or forge) remelted ingot into forging quality billet or bloom.
- Final processing cost includes hot rolling or forging to final size and heat treatment.

Environmental Benefits

Austenitizing furnaces burn natural gas to generate heat. One by-product of the combustion process is CO₂. Because the new technology (thermal mechanical treatment) eliminates the need to austenitize bar products, use of austenitizing furnaces can be curtailed and generation of CO₂ will be reduced compared to the production of conventional martensitic stainless steels. Moreover, the environmental benefits of 521-A production compared to that of IN 718 is even greater. IN 718 is commonly made by vacuum induction melting, which is an energy intensive process that consumes large quantities of electricity. By replacing vacuum induction melted IN 718 with air-melted 521-A, it is estimated that energy consumption during melting could be reduced by one-half and greenhouse gases released at the point of electricity generation, similarly curtailed.

Metrics Summary

The installed unit for the proposed technology (521-A) is pounds per year. The installed unit for the comparable competing technology is pounds per year, also.

The energy consumption for the proposed unit is 423 Btu/yr./unit. The energy consumption for the comparable competing unit is 798 Btu/yr./unit and 1208 Btu/yr./unit for AISI 422 and IN 718, respectively. Please see below for a discussion of the assumptions and references used to calculate the energy consumed.

The total energy consumed during processing and heat treating of bar products made from AISI 422, IN 718 and 521-A was taken to be the sum of the energy consumed during soaking, aging, austenitizing and tempering (second aging in the case of IN 718). Results are presented in Table D4.

Assumptions used to calculate the total energy savings include:

- Heat losses, e.g., through the furnace walls, are constant in all cases.
- The specific heat is taken to be 0.105 BTU / lb. °F for all temperature ranges of interest and for all three materials.
- The specific energy consumed (per pound basis) during heat treatment is proportional to the desired heating temperature.
- The specific energy consumed during heat treatment is proportional to the square root of the total time spent at the temperature of interest.

Table D4. Estimated energy consumption (BTU/lb.) to soak, age, austenitize and temper bar made from AISI 422, IN 718, and 521-A. Total energy savings for each conventional alloy versus 521-A is given as well as the estimated net energy savings by 2010.

Alloy	Soak	Age	Austenitize	Temper	Total energy used	Energy saved vs. 521-A ¹	Estimated number of lb. used ² in U.S. by 2010	Energy Savings by 2010 (BTU)
AISI 422 ³	282	--	275	242	798	47%	-20,000,000	-1.6x10 ¹⁰
IN 718 ⁴	282	386	--	540	1208	65%	-20,000,000	-2.4x10 ¹⁰
521-A ⁵	282	--	--	141	423	--	40,000,000	1.7 x10 ¹⁰
Net Energy Savings by 2010 (BTU)								2.3 x10 ¹⁰

¹ Energy saved (%) if 521-A were used instead of listed conventional material

² A negative number indicates amount of product not used

³ AISI 422: soak: 1950°F (2 hr.); age: n/a; austenitize: 1900°F (2 hr.); temper: 1200°F (4 hr.)

⁴ IN 718: soak: 1950°F (2 hr.); age: 1350°F (8 hr.); austenitize: n/a; temper: 1200°F (20 hr.)

⁵ 521-A: soak: 1950°F (2 hr.); austenitize: n/a; temper: 1000°F (2 hr.)