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(54) HIGH STRENGTH STEEL ALLOYS WITH DUCTILITY CHARACTERISTICS

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C22C 38/08	(2006.01)
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C21D 8/02	(2006.01)

(52) **U.S. Cl.**

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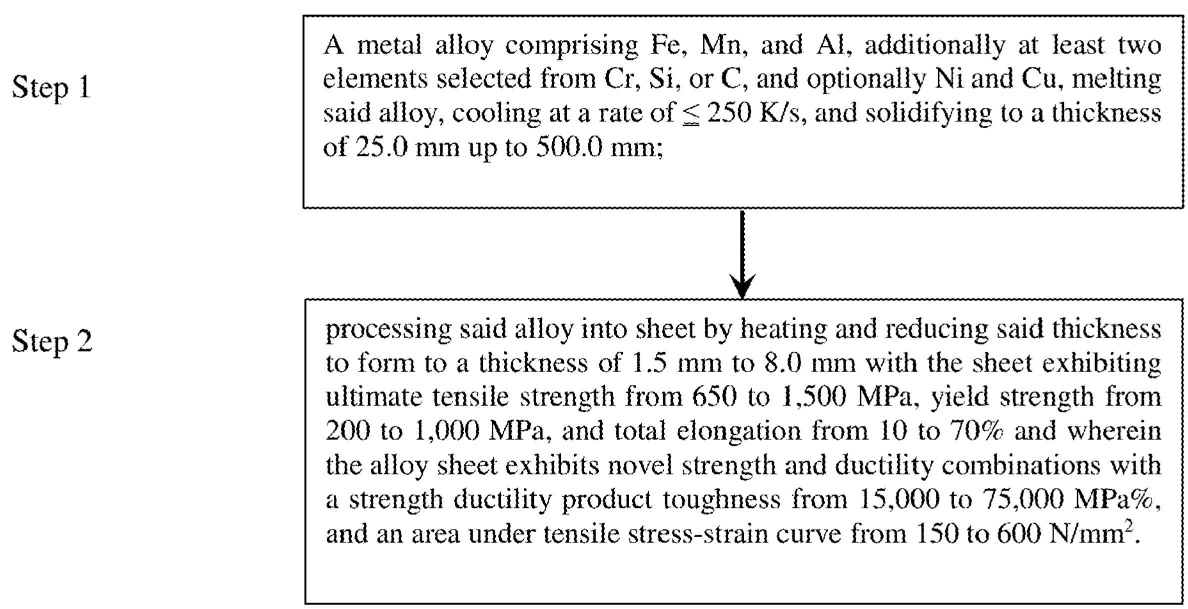
(57) **ABSTRACT**

A new class of advanced high strength steel alloys with ductility characteristics such as high impact toughness and improved resistance to penetration, crack resistance and crack propagation.



Step 1

A metal alloy comprising Fe, Mn, and Al, additionally at least two elements selected from Cr, Si, or C, and optionally Ni and Cu, melting said alloy, cooling at a rate of $\leq$ 250 K/s, and solidifying to a thickness of 25.0 mm up to 500.0 mm;

↓

Step 2

processing said alloy into sheet by heating and reducing said thickness to form to a thickness of 1.5 mm to 8.0 mm with the sheet exhibiting ultimate tensile strength from 650 to 1,500 MPa, yield strength from 200 to 1,000 MPa, and total elongation from 10 to 70% and wherein the alloy sheet exhibits novel strength and ductility combinations with a strength ductility product toughness from 15,000 to 75,000 MPa%, and an area under tensile stress-strain curve from 150 to 600 N/mm^2.

FIG. 1

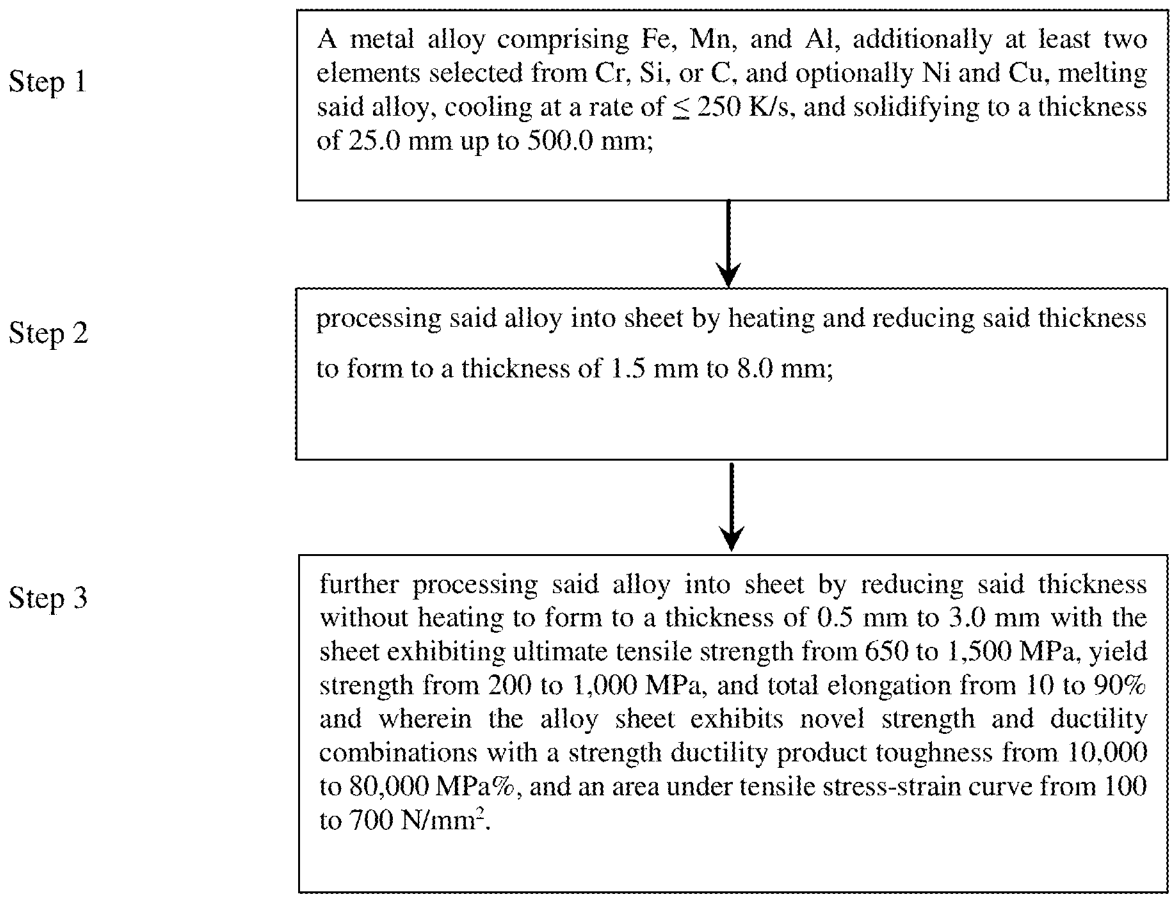

Step 1
A metal alloy comprising Fe, Mn, and Al, additionally at least two elements selected from Cr, Si, or C, and optionally Ni and Cu, melting said alloy, cooling at a rate of ≤ 250 K/s, and solidifying to a thickness of 25.0 mm up to 500.0 mm;
Step 2
processing said alloy into sheet by heating and reducing said thickness to form to a thickness of 1.5 mm to 8.0 mm;
Step 3
further processing said alloy into sheet by reducing said thickness without heating to form to a thickness of 0.5 mm to 3.0 mm with the sheet exhibiting ultimate tensile strength from 650 to 1,500 MPa, yield strength from 200 to 1,000 MPa, and total elongation from 10 to 90% and wherein the alloy sheet exhibits novel strength and ductility combinations with a strength ductility product toughness from 10,000 to 80,000 MPa%, and an area under tensile stress-strain curve from 100 to 700 N/mm^2.

FIG. 2

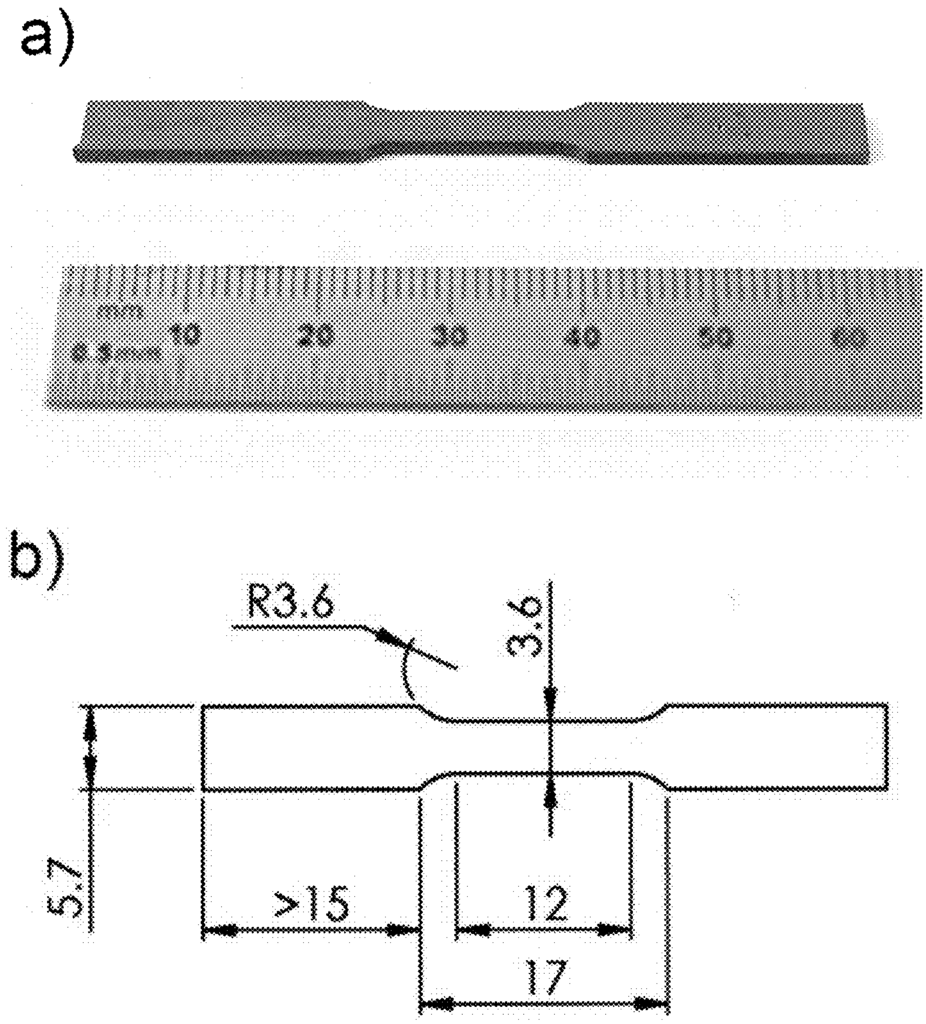


FIG. 3

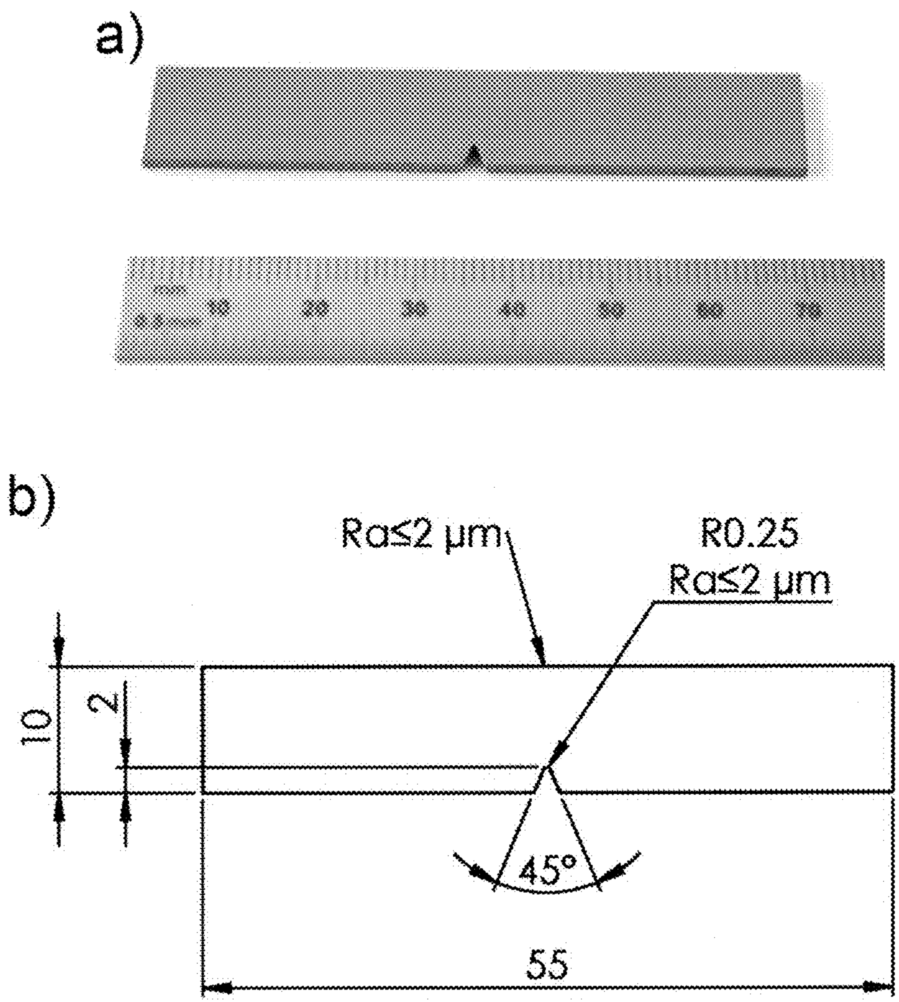


FIG. 4

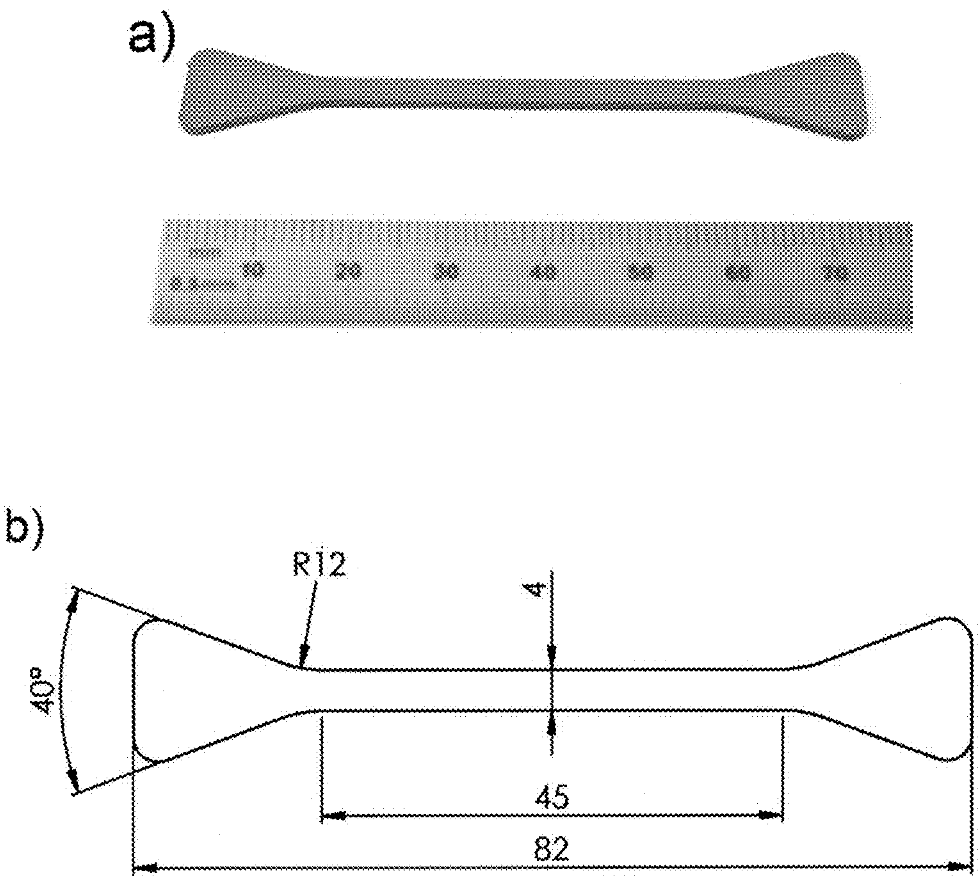


FIG. 5

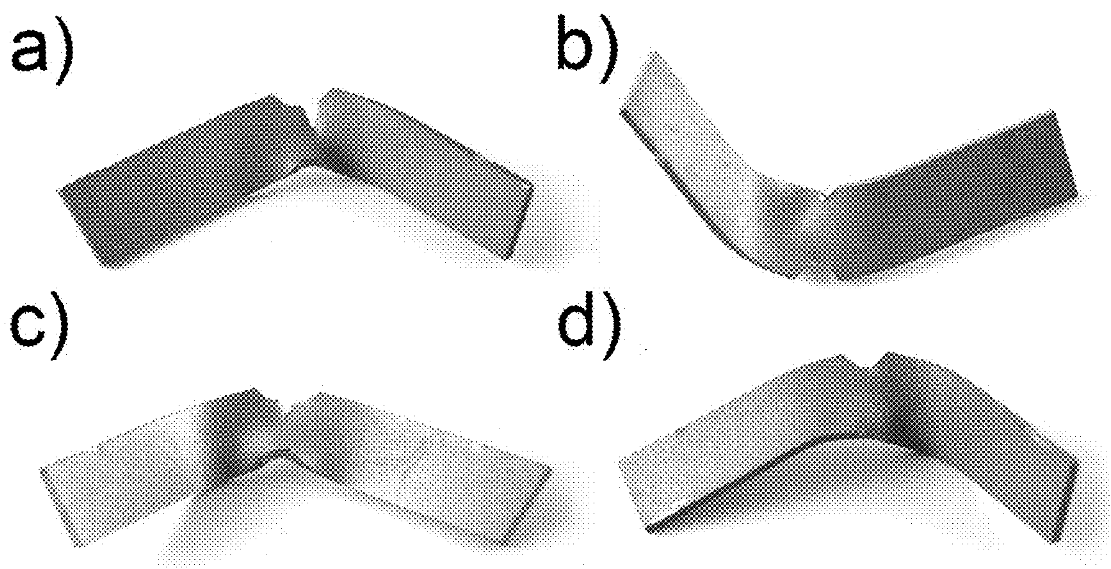


FIG. 6

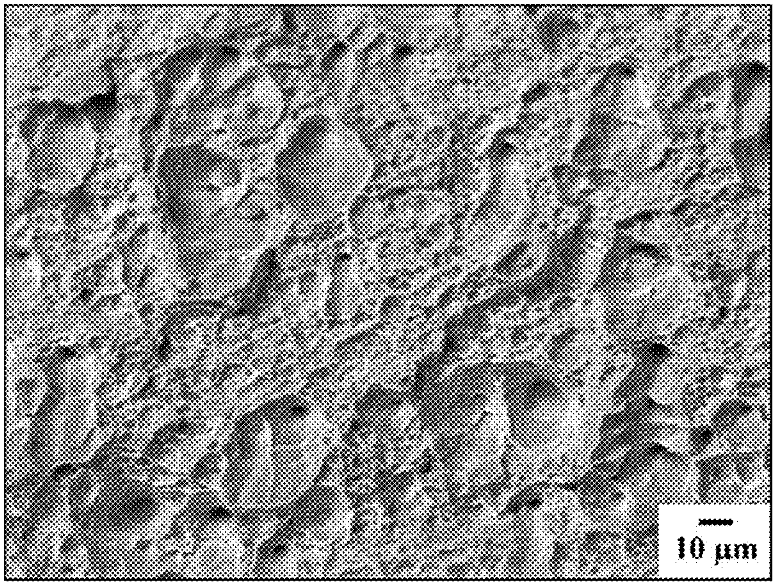


FIG. 7

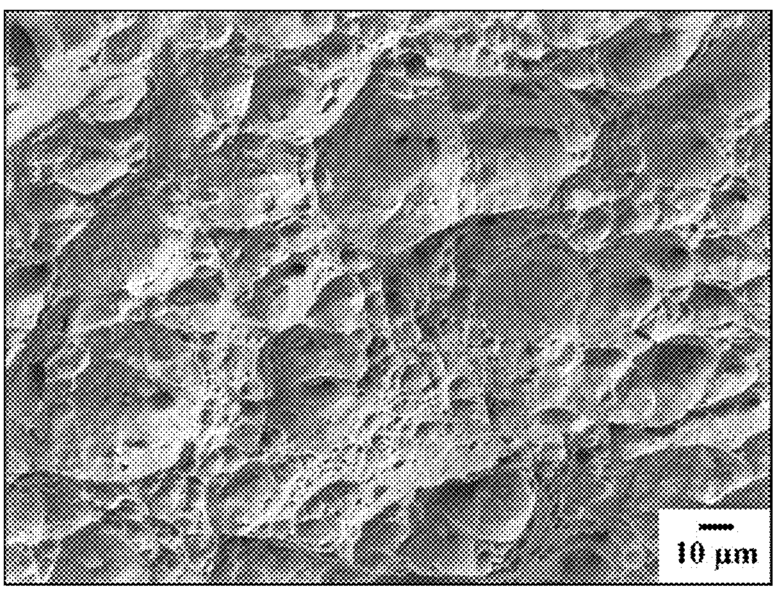


FIG. 8

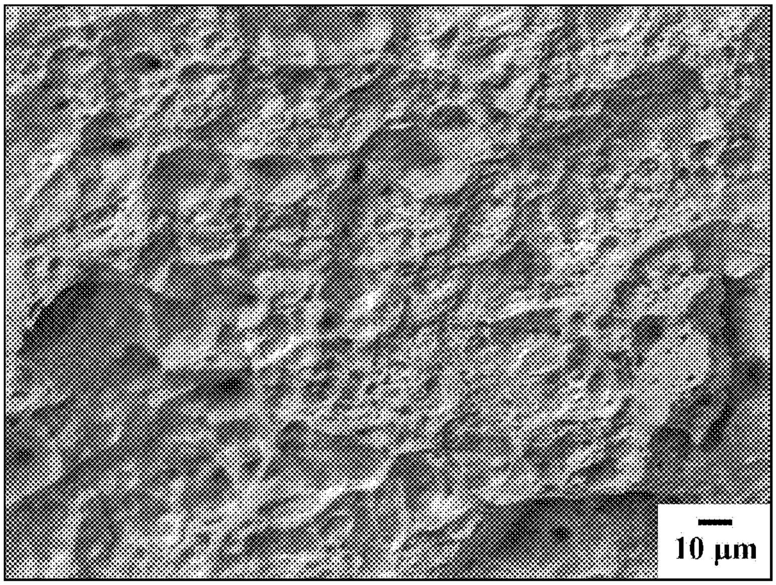


FIG. 9

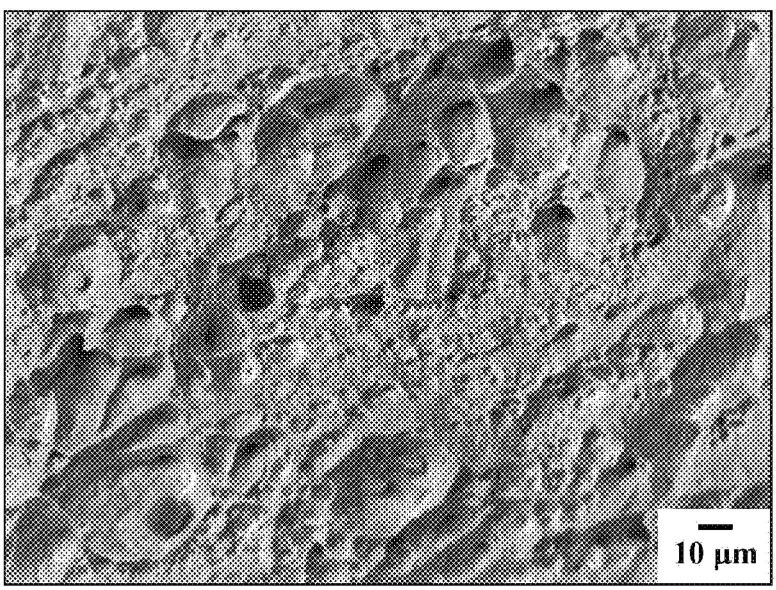


FIG. 10

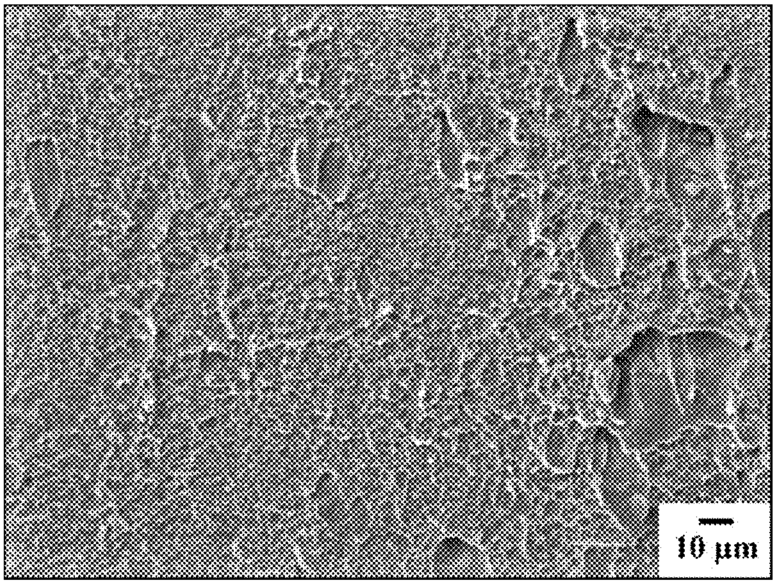


FIG. 11

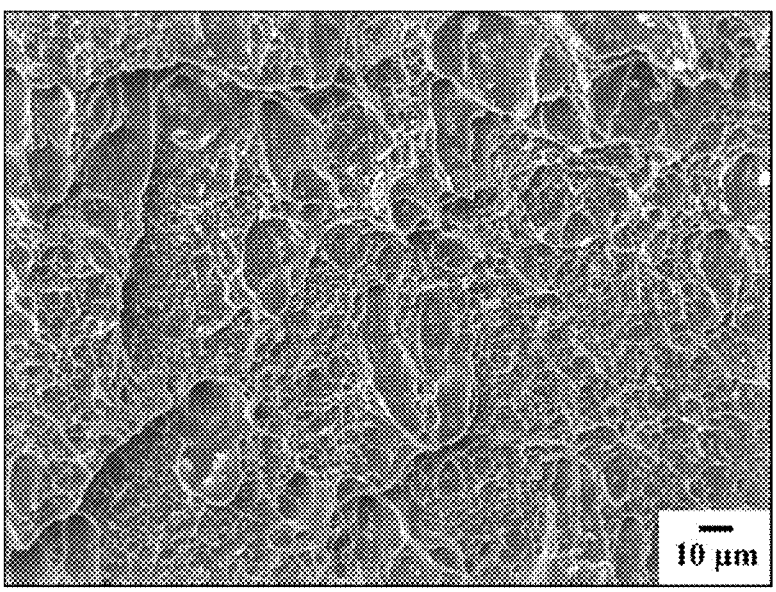


FIG. 12

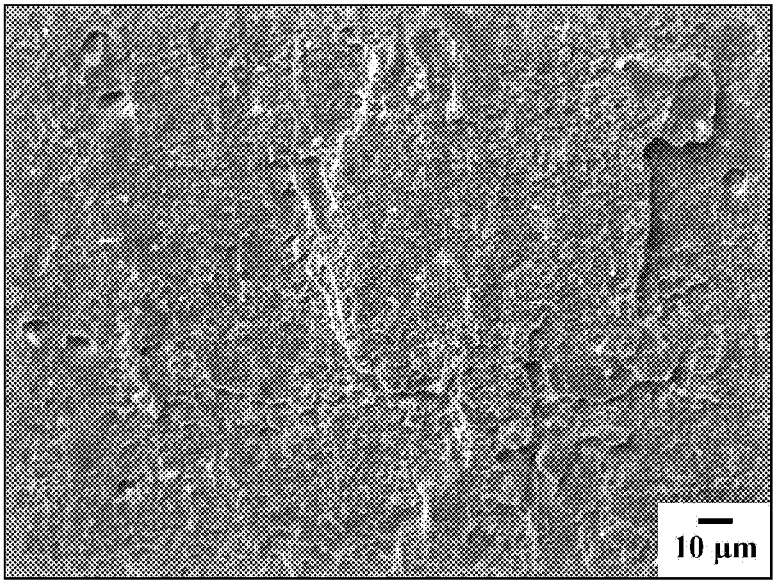


FIG. 13

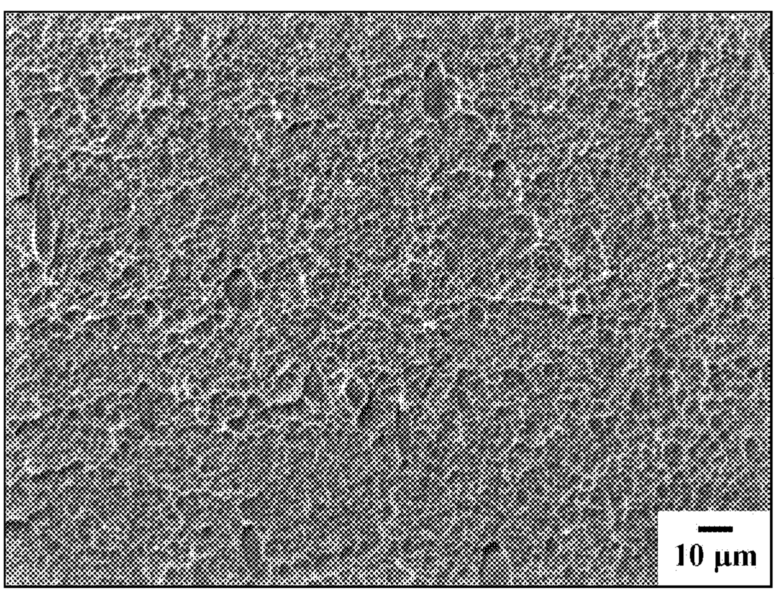


FIG. 14

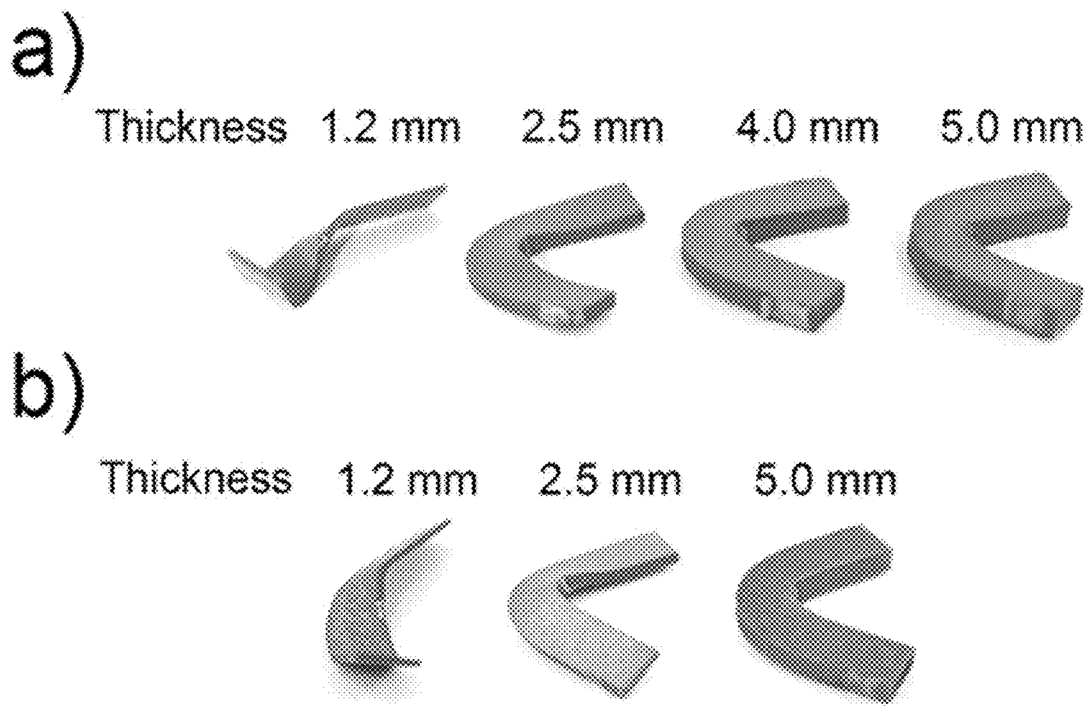


FIG. 15

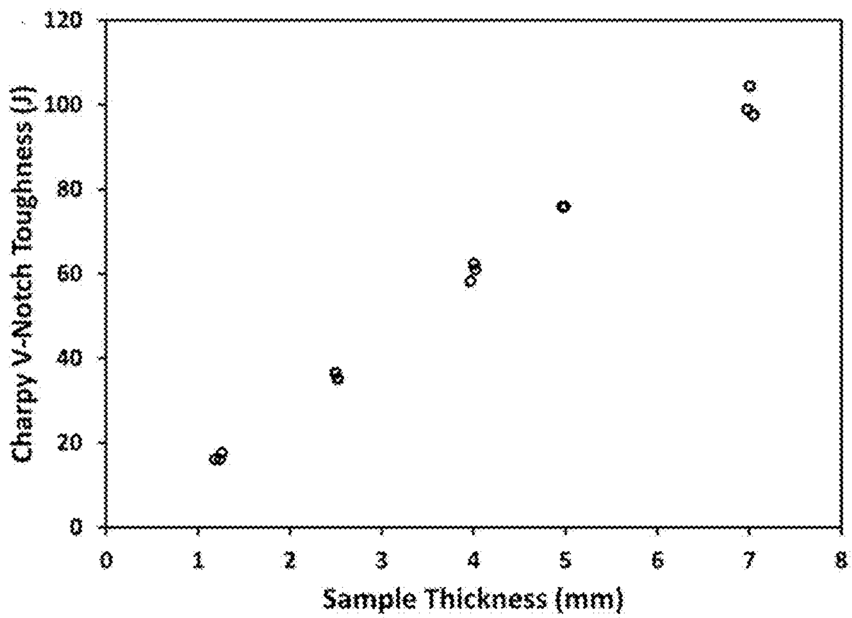

Charpy V-Notch Toughness (J)
0
20
40
60
80
100
120
0
1
2
3
4
5
6
7
8
Sample Thickness (mm)

FIG. 16

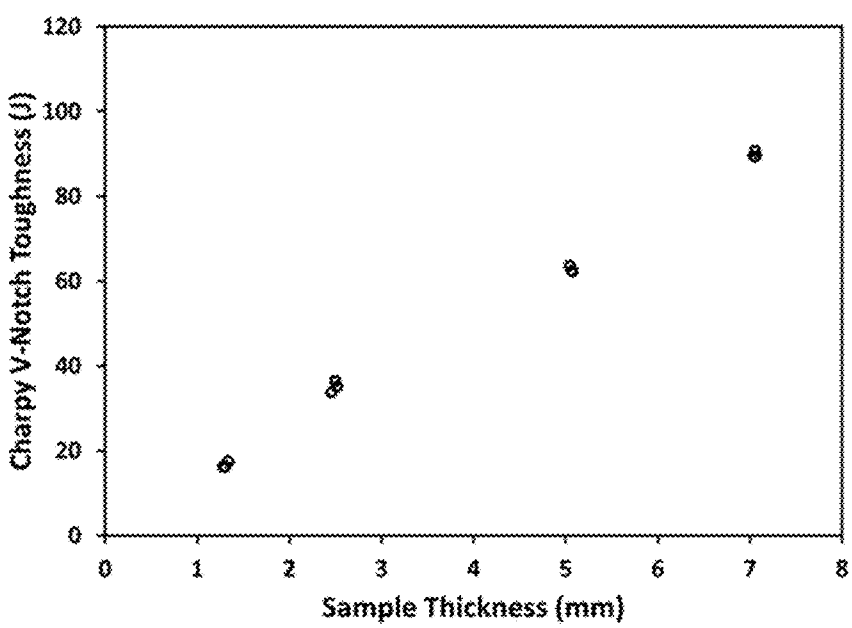

Charpy V-Notch Toughness (J)
0
20
40
60
80
100
120
0
1
2
3
4
5
6
7
8
Sample Thickness (mm)

FIG. 17

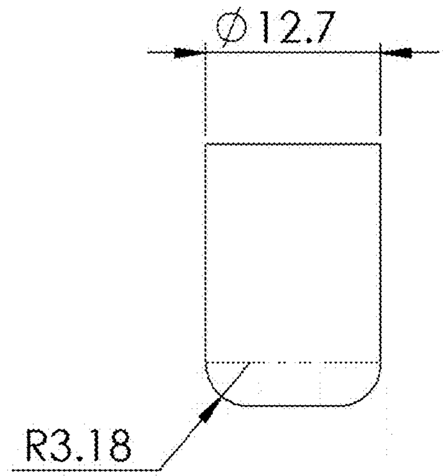


FIG. 18

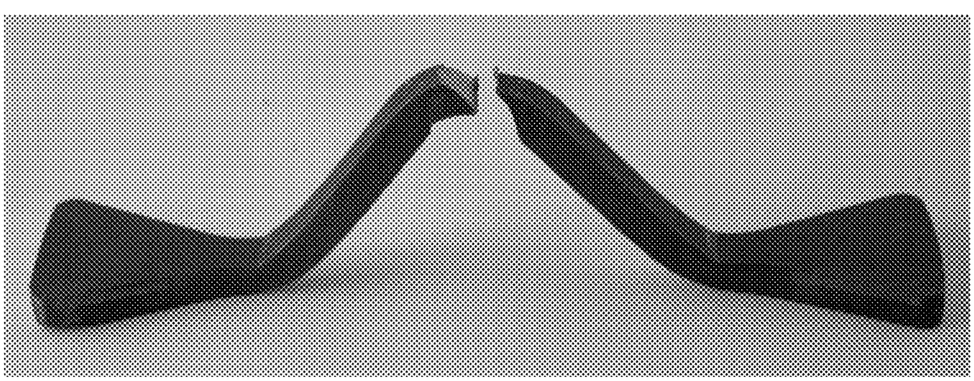


FIG. 19

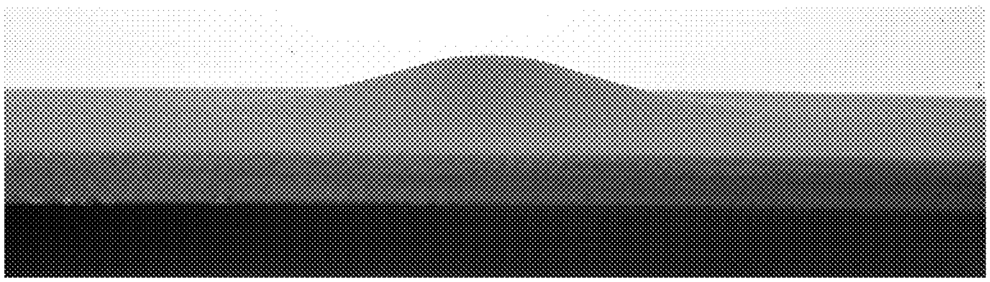


FIG. 20

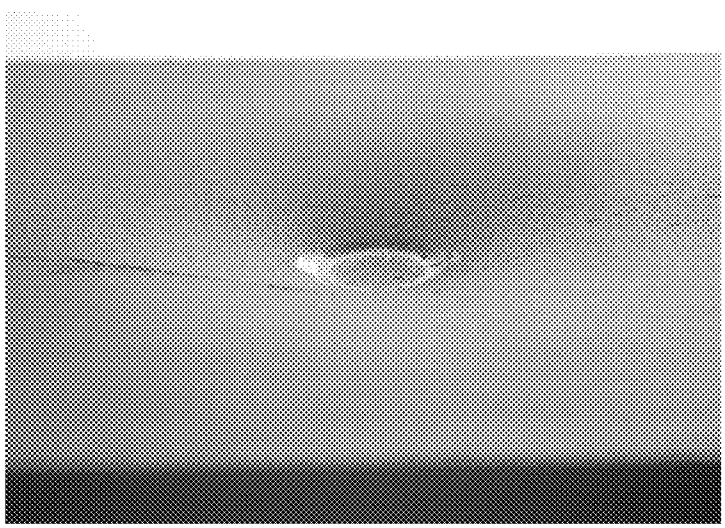


FIG. 21

HIGH STRENGTH STEEL ALLOYS WITH DUCTILITY CHARACTERISTICS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application 62/684,869 filed Jun. 14, 2018 which is fully incorporated herein by reference.

FIELD OF INVENTION

[0002] This application deals with a new class of advanced high strength steel alloys with ductility characteristics such as high impact toughness and improved resistance to penetration, crack initiation and crack propagation.

BACKGROUND

[0003] Toughness as an engineering property can be thought of as the work energy needed to cause failure in a material. The higher the work required to cause failure by a method, the higher the toughness of the material. Toughness in materials is becoming increasingly important across many sectors, especially where tough materials can be used to improve safety. In the automotive industry, relatively high toughness materials are seeing use in so-called crumple zones to reduce the energy that enters the passenger compartment during a collision. Using relatively high toughness materials, gauge thicknesses can be reduced in automobiles in parts where energy absorption is needed to protect passengers, increasing fuel efficiency without compromising safety. These relatively high toughness materials can also be used for road barriers to keep out-of-control vehicles from leaving the roadway or entering the opposing traffic by absorbing energy from the vehicle and safely stopping it. The automotive industry is not alone in the need for relatively high toughness materials, however. The safety of cargo transported overland by rail and on waterways by ships can also be improved with relatively high toughness materials. In recent years, several high-profile incidents where cargo vessels were damaged during collisions or derailments have occurred that have resulted in significant loss of life, property, and cargo. New regulations have been introduced to lessen the probability and impact of such events, and the use of relatively high toughness materials to ensure improved cargo containment is one option available. By increasing the toughness of materials for these shipping containers, cargo can be kept inside the container during such an event and will reduce environmental impact and loss of life or property damage that could result from wayward cargo. Relatively high toughness materials therefore provide many industries the opportunity to improve fuel and cargo efficiency while maintaining or improving safety.

[0004] Advanced High Strength Steels (AHSS's) are those classes of materials whose mechanical properties are superior to the conventional steels. Conventional mild steel has a relatively simple ferritic microstructure; it typically has relatively low carbon content and minimal alloying elements, is readily formed, and is especially sought for its ductility. Widely produced and used, mild steel often serves as a baseline for comparison of other materials. Conventional low- to high-strength steels include IF (interstitial free), BH (bake hardened), and HSLA (high-strength low-alloy). These steels generally have a yield strength of less than 550 MPa and ductility that decreases with increased strength. Higher strength steels are more complex and include such grades as dual phase (DP), complex phase (CP) and transformation induced plasticity (TRIP) steels. The development of advanced high strengths steel has been a challenge since increased strength often results in reduced ductility, cold formability, and toughness.

[0005] Toughness can be measured by a variety of methods, with each method characterizing a material response to a specific condition. Methods to characterize toughness include tensile testing, bulk fracture testing, and Charpy impact testing including V-notched and un-notched specimen geometries. Tensile testing is one of the most widely used methods for mechanical properties evaluation and generally performed by applying load to a sample with a reduced section by a moving crosshead until the sample fails. The displacement rate of the crosshead in tensile testing is generally kept constant or near constant, resulting in a relatively narrow range of strain rates throughout the test. Tensile testing can provide a measure of toughness by calculating the integral of the engineering stress –engineering strain curve and is related to the work required to break the sample in tension and estimated by multiplying the ultimate tensile strength by the total elongation (strength-ductility product). Toughness requirements are unique for each application and a selection of testing method depends on where the application is likely to see failure in a manner similar to particular test condition.

SUMMARY

[0006] A method to achieve a strength/ductility characteristic in a metal comprising:

[0007] a. supplying a metal alloy comprising at least 70 atomic percent Fe, at least 9.0 atomic percent Mn, at least 0.4 atomic percent Al, and at least two elements selected from Cr, Si or C, melting and cooling at a rate of ≤250 K/s to a thickness of 25.0 mm to 500.0 mm;

[0008] b. processing said alloy into sheet by heating and reducing said thickness to form to a thickness of 1.5 mm to 8.0 mm wherein the sheet exhibits an ultimate tensile strength (TS) of 650 MPa to 1500 MPa, a yield strength (YS) at 0.2% offset of 200 MPa to 1,000 MPa and an elongation (E) from 10% to 70%, wherein the alloy further indicates a strength ductility product (TS×E) in the range of 15,000 MPa % to 75,000 MPa %.

[0009] A method to achieve a strength/ductility characteristic in a metal comprising:

[0010] a. supplying a metal alloy comprising at least 70 atomic percent Fe, at least 9.0 atomic percent Mn, at least 0.4 atomic percent Al, and at least two elements selected from Cr, Si or C, melting and cooling at a rate of ≤250 K/s to a thickness of 25.0 mm to 500.0 mm;

[0011] b. processing said alloy into sheet by heating and reducing said thickness to form to a thickness of 1.5 mm to 8.0 mm;

[0012] c. processing said alloy into sheet by reducing said thickness without heating to form to a thickness of 0.5 mm to 3.0 mm wherein the sheet is annealed and exhibits an ultimate tensile strength (TS) of 650 MPa to 1500 MPa, a yield strength (YS) at 0.2% offset of 200 MPa to 1000 MPa and an elongation (E) from 10.0% to 90.0%, wherein the alloy further indicates a strength ductility product (TS×E) in the range of 10,000 MPa % to 80,000 MPa %.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The detailed description below may be better understood with reference to the accompanying FIG.s which are provided for illustrative purposes and are not to be considered as limiting any aspect of this invention.

[0014] FIG. **1** Summary on steps towards toughness achievements in alloys herein for the method herein where the alloy at an initial thickness of 25.0 mm to 500.0 mm is heated while reduced in thickness to a reduced thickness of 1.5 mm to 8.0 mm.

[0015] FIG. **2** Summary on steps towards toughness achievements in alloys herein where the alloy at an initial thickness of 25.0 mm to 500.0 mm is processed into sheet by heating and reducing thickness to 1.5 mm to 8.0 mm and then further reduced to a thickness of 0.5 to 3.0 mm without heating and to provide the indicated properties.

[0016] FIG. **3** Tensile testing geometry; (a) Example of the tensile specimen before testing, and (b) Schematic illustration (all dimensions are in mm).

[0017] FIG. **4** Charpy V-notched testing geometry; (a) Example of the Charpy V-notched specimen before testing, and (b) Schematic illustration (all dimensions are in mm).

[0018] FIG. **5** Bulk fracture testing geometry; (a) Example of the bulk fracture specimen before testing, and (b) Schematic illustration (all dimensions are in mm).

[0019] FIG. **6** Examples of the unbroken Charpy V-notch specimen after testing from (a) Alloy 1, (b) Alloy 2, (c) Alloy 3, and (d) Alloy 4.

[0020] FIG. **7** SEM images of the fracture surface in the Charpy V-notch specimen from Alloy 7 after testing.

[0021] FIG. **8** SEM images of the fracture surface in the Charpy V-notch specimen from Alloy 9 after testing.

[0022] FIG. **9** SEM images of the fracture surface in the Charpy V-notch specimen from Alloy 19 after testing.

[0023] FIG. **10** SEM images of the fracture surface in the Charpy V-notch specimen from Alloy 20 after testing.

[0024] FIG. **11** SEM images of the fracture surface in the bulk fracture test specimen from Alloy 7 after testing.

[0025] FIG. **12** SEM images of the fracture surface in the bulk fracture test specimen from Alloy 9 after testing.

[0026] FIG. **13** SEM images of the fracture surface in the bulk fracture test specimen from Alloy 19 after testing.

[0027] FIG. **14** SEM images of the fracture surface in the bulk fracture test specimen from Alloy 20 after testing.

[0028] FIG. **15** Examples of unbroken specimens with different thicknesses; (a) From Alloy 7, and (b) From Alloy 9.

[0029] FIG. **16** Charpy V-notch toughness as a function of thickness in Alloy 7.

[0030] FIG. **17** Charpy V-notch toughness as a function of thickness in Alloy 9.

[0031] FIG. **18** Drawing of the impactor utilized during drop impact testing (all dimensions are in mm).

[0032] FIG. **19** A 4 mm thick bulk fracture test specimen from Alloy 24 after testing.

[0033] FIG. **20** Side view of a 4 mm thick drop impact test specimen from Alloy 24 hot band after testing.

[0034] FIG. **21** View of the impact location of a 4 mm thick drop impact test specimen from Alloy 24 hot band after testing.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0035] Alloys herein can be produced by different methods of casting including but not limited to continuous casting, thin slab casting, thick slab, and bloom casting at 25.0 to 500.0 mm in thickness with achievement of advanced property combinations by subsequent post-processing. After casting hot rolling is applied to produce thickness ranges from 1.5 to 8.0 mm. Cold rolling may be additionally applied to the hot rolled sheet to produce thickness ranges from 0.5 to 3.0 mm. Annealing may or may not be applied to produced hot rolled and/or cold rolled sheet or plate. FIG. **1** and FIG. **2** provides property ranges for the alloys herein processed in a sheet form. The property ranges in this figure is collected from the ensuing description of the alloys and associated testing.

[0036] FIG. **1** and FIG. **2** illustrate the toughness achievements in alloys herein. In Step **1** in FIG. **1** and FIG. **2**, the preferred starting condition is to supply a metal alloy with Fe, Mn and Al, at least two elements selected from Cr, Si, or C, and optionally, Ni and/or Cu. The alloy chemistry is melted, cooled at a rate of ≤250 K/s, and solidified to a thickness of 25.0 mm and up to 500.0 mm. The casting process can be done in a wide variety of processes including ingot casting, bloom casting, continuous casting, thin slab casting, thick slab casting, belt casting etc. Preferred methods would be continuous casting in sheet form by thin slab casting or thick slab casting. To produce alloys herein in a sheet form, the cast processes can vary widely depending on specific manufacturing routes and specific targeted goals. As an example, consider thick slab casting as one process route to get to sheet product. The alloy would be preferably cast going through a water-cooled mold typically in a thickness range of 150 mm to 350 mm in thickness. Another example would be to preferably process the cast material through a thin slab casting process where casting is typically from 25 to 150 mm in thickness by going through a water-cooled mold. Note that bloom casting would be similar to the examples above, but higher thickness might be cast typically from 200 to 500 mm thick.

[0037] Step **2** in FIG. **1** corresponds to processing said sheet with an initial cast thickness of 25.0 mm to 500.0 mm and reducing to a thickness from 1.5 to 8.0 mm while heating. The processing of the cast material in Step **1** into sheet form can be done by heating, such as by hot rolling, forming a hot band/plate by various methods including roughing mill hot rolling, finishing mill hot rolling, and Steckel mills. The preferred temperature range for such heating is in the range of 700° C. up to the solidus temperature of the alloy. To optimize properties of the hot band after it is produced, the hot band may be additionally heat treated by continuous methods including anneal and pickle lines and continuous annealing lines and batch annealing furnaces. Preferably, sheet material from alloys herein where the thickness reduction has been achieved in the presence of heating has an ultimate tensile strength from 650 to 1500 MPa, a yield strength (YS) at 0.2% offset from 200 MPa to 1,000 MPa, a total elongation from 10% to 70%. Calculated characteristics of toughness based on tensile testing data are represented by the strength/elongation product from 15,000 MPa % to 75,000 MPa % and can be further characterized as having an area under tensile curve from 150 to 600 N/mm^2 (Modulus of toughness).

[0038] Step **2** in FIG. **2** corresponds to processing said alloy into sheet with heating and reducing the thickness of the alloy from an initial thickness of 25.0 mm to 500.0 mm to form a thickness of 1.5 mm to 8.0 mm. The processing of the cast material in Step **1** of FIG. **2** into an initial sheet form at a thickness of 25.0 mm to 500.0 mm can again be done by heating, such as by hot rolling, forming a hot band by various methods including roughing mill hot rolling, finishing mill hot rolling, and Steckel mills. Again, the preferred temperature range for such heating is in the range of 700° C. up to the solidus temperature of the alloy.

[0039] Step **3** in FIG. **2** is therefore preferably done through cold rolling to produce cold rolled sheet with typical thickness from 0.5 to 3.0 mm thick. Note that cold rolling is done without external heat applied to the sheet before or after the reduction process but internal heating/adiabatic heating during the reduction process would be inherent in the process. Cold reduction can be applied at various reductions per pass, variable number of passes and in different mills including tandem mills, Z-mills, Sendzimir mills, and reversing mills. After cold rolling to produce a targeted gauge from 0.5 to 3.0 mm thick, the cold rolled material, which has reduced ductility remaining since, ductility is reduced due to the deformation/gauge reduction, can be preferably annealed to increase the ductility lost from the cold rolling process either partially or completely. Heat treatment, if applied, will be from 600° C. up to the melting point (defined as the solidus temperature). Time for heat treatment can vary depending on the equipment utilized, the thickness of the material heat treated, and the goal of the heat treatment (partial recrystallization, full recrystallization, normalization, heat treatment etc.) but is preferably in the range from 1 minute to 72 hours. Preferably, sheet material from alloys herein by the procedure in FIG. **2** has an ultimate tensile strength from 650 to 1500 MPa, a yield strength at 0.2% offset from 200 MPa to 1,000 MPa, a total elongation from 10 to 90%. Calculated characteristics of toughness based on tensile testing data are represented by the strength/elongation product from 10,000 MPa % to 80,000 MPa %, and may be further characterized by an area under tensile curve from 100 to 700 N/mm^2 (Modulus of toughness).

[0040] Sheet toughness produced from FIG. **1** or FIG. **2** was preferably evaluated by drop impact testing, bulk fracture testing, and Charpy V-notch impact testing. Drop impact testing was used to gauge sheet material toughness and its resistance to penetration. This technique employs a weight dropped from a specific height onto a planar sample that is biaxially constrained. The direction of movement of the impactor is normal to both biaxially constrained directions and in the same direction as the material's thickness. The drop impact testing technique tests a biaxially constrained material's resistance to penetration by an object moving normal to its surface. Preferably, the sheet material herein produced via the method in FIG. **1** exhibits a drop impact toughness of 100 J to 1250 J. Additionally, the range of thickness normalized drop impact toughness is from 75 J/mm to 160 J/mm. Thickness normalized drop impact toughness is the ratio of the toughness measured in Joules from the drop impact test divided by the thickness of the particular sample tested in mm. Preferably, the sheet material herein produced via the method in FIG. **2** exhibits a drop impact toughness of 40 to 700 J. Additionally, the range of thickness normalized drop impact toughness is from 75 to 250 J/mm. As the material gauge is increased from 1.5 to 8.0 mm in thickness in FIG. **1** or increased from 0.5 to 3.0 mm in FIG. **2**, it is contemplated that the drop impact toughness values will increase accordingly.

[0041] Bulk fracture testing has been developed to test material toughness to simulate material performance under specific collision-like loading events. It characterizes a resistance to crack initiation. The bulk fracture sample is dynamically loaded perpendicular to the thickness of the material. The sample ends are held fixed in place during the test. This load deforms the sample out of plane until the sample fails by a plastic instability (necking in ductile metals), similar to failure by tensile loading. Preferably, the sheet material herein produced via the method in FIG. **1** exhibits a bulk fracture toughness depending on sheet thickness from 10 to 400 J. Additionally, the range of thickness normalized bulk fracture toughness is from 5 to 50 J/mm. Preferably, the sheet material herein produced via the method in FIG. **2** exhibits a bulk fracture toughness from 2 to 175 J. Additionally, the range of thickness normalized bulk fracture toughness from 1 to 60 J/mm. Thickness normalized bulk fracture toughness is the ratio of the toughness measured in Joules from the bulk fracture test divided by the thickness of the particular sample tested in mm. As the material gauge is increased from 1.5 to 8.0 mm in thickness in FIG. **1** or increased from 0.5 to 3.0 mm in FIG. **2**, it is contemplated that the bulk fracture toughness values will increase accordingly.

[0042] Charpy impact testing is preferably performed by the dynamic loading of a sample by a swinging hammer starting from a known height and distance from the center of rotation. The ends of the samples in Charpy impact testing are free and the loading of the sample is similar to a three-point bend test. The total energy of the moving hammer is known and the energy lost in the impact event with the sample can be measured by the rotation angle of the hammer after impact. In Charpy V-notch testing the sample has a pre-machined stress concentration point at the V-notch tip which helps encourage crack nucleation. In this test, the hammer strikes the side opposite the machined notch. Charpy V-notch impact testing measures the work required to plastically deform the sample as well as crack nucleation and propagation. Preferably, the sheet material herein produced via the method in FIG. **1** exhibits a Charpy V-notched toughness of 10 to 150 J. Additionally, the range of thickness normalized Charpy V-Notched toughness is from 5 to 25 J/mm. Preferably, the sheet material herein produced via the method in FIG. **2** exhibits a Charpy V-notched toughness of 0.5 to 75 J. Additionally, the range of thickness normalized Charpy V-Notched toughness from 0.5 to 25 J/mm. Thickness normalized Charpy V-Notched is the ratio of the toughness measured in Joules from the Charpy V-Notched test divided by the thickness of the particular sample tested in mm.

Main Body

Alloys

[0043] The chemical composition of the alloys herein is shown in Table 1, which provides the preferred atomic ratios utilized.

TABLE 1

Chemical Composition Of Alloys (Atomic %)								
Alloy	Fe	Mn	Al	Cr	Si	C	Ni	Cu
Alloy 1	70.92	14.10	5.11	2.50	4.87	0.75	1.13	0.62
Alloy 2	77.35	11.51	4.42	—	0.76	2.55	2.56	0.85
Alloy 3	79.85	12.04	2.42	—	0.79	2.67	1.34	0.89
Alloy 4	77.85	12.04	4.42	—	0.79	2.67	1.34	0.89
Alloy 5	75.85	12.04	6.42	—	0.79	2.67	1.34	0.89
Alloy 6	75.11	12.04	3.65	2.63	5.13	0.79	—	0.65
Alloy 7	74.05	12.04	4.71	2.63	5.13	0.79	—	0.65
Alloy 8	72.13	12.04	6.63	2.63	5.13	0.79	—	0.65
Alloy 9	75.03	12.04	4.38	2.63	5.13	0.79	—	—
Alloy 10	73.76	12.04	5.65	2.63	5.13	0.79	—	—
Alloy 11	74.42	12.04	4.34	2.63	5.13	0.79	—	0.65
Alloy 12	75.21	12.04	4.34	2.63	5.13	—	—	0.65
Alloy 13	73.63	12.04	4.34	2.63	5.13	1.58	—	0.65
Alloy 14	76.42	12.04	4.34	2.63	3.13	0.79	—	0.65
Alloy 15	78.42	12.04	4.34	2.63	1.13	0.79	—	0.65
Alloy 16	75.76	14.00	4.00	1.02	4.43	0.79	—	—
Alloy 17	74.65	12.04	4.76	2.63	5.13	0.79	—	—
Alloy 18	75.44	12.04	4.76	2.63	5.13	—	—	—
Alloy 19	73.86	12.04	4.76	2.63	5.13	1.58	—	—
Alloy 20	76.65	12.04	4.76	2.63	3.13	0.79	—	—
Alloy 21	78.65	12.04	4.76	2.63	1.13	0.79	—	—
Alloy 22	76.15	9.16	6.14	2.63	5.13	0.79	—	—
Alloy 23	74.37	13.13	4.00	2.63	4.43	0.79	—	0.65
Alloy 24	74.26	13.57	4.00	2.63	4.43	0.79	—	0.32
Alloy 25	74.15	14.00	4.00	2.63	4.43	0.79	—	—
Alloy 26	75.68	13.13	4.00	1.32	4.43	0.79	—	0.65
Alloy 27	75.57	13.57	4.00	1.32	4.43	0.79	—	0.32
Alloy 28	75.46	14.00	4.00	1.32	4.43	0.79	—	—
Alloy 29	77.00	13.13	4.00	—	4.43	0.79	—	0.65
Alloy 30	76.89	13.57	4.00	—	4.43	0.79	—	0.32
Alloy 31	76.78	14.00	4.00	—	4.43	0.79	—	—
Alloy 32	73.52	12.14	4.61	3.26	4.07	2.11	—	0.29
Alloy 33	75.69	14.16	3.20	4.59	—	1.51	0.37	0.48
Alloy 34	70.45	16.85	0.87	1.49	6.22	1.72	0.55	1.85
Alloy 35	78.86	14.41	2.68	0.29	0.87	1.15	0.78	0.96
Alloy 36	76.83	13.67	0.42	—	2.78	0.38	3.47	2.45
Alloy 37	75.57	11.33	5.55	6.22	0.35	0.98	—	—
Alloy 38	72.85	16.98	1.70	2.76	3.03	1.13	—	1.55
Alloy 39	74.19	15.64	1.70	2.76	3.03	1.13	—	1.55
Alloy 40	74.25	16.31	1.26	2.76	3.03	1.13	—	1.26

[0044] With regards to the above, and as can be seen from Table 1, preferably, when Fe is present at a level of greater than or equal to 70 at. % with Mn and Al, at least two elements are selected from Cr, Si, or C, and optionally, Ni and/or Cu to provide a formulation of elements that totals 100 atomic percent. More preferably, the alloys herein can be described as comprising, consisting essentially of, or consisting of the following elements at the indicated atomic percent: Fe (70 to 80 at. %), Mn (9.0 to 17.0 at. %), Al (0.4 to 6.7 at. %), at least two elements selected from Cr, Si, or C in the following ranges, Cr (0.2 to 6.3 at. %), Si (0.3 to 6.3 at. %), and C (0.3 to 2.7 at. %), and optionally Ni (0.3 to 3.5 at. %) and/or Cu (0.2 to 2.5 at. %). The level of impurities of other elements is in the range of 0 to 5,000 ppm, or 0 to 4000 ppm, or 0 to 3000 ppm, or 0 to 2000 ppm, or 0 to 1000 ppm. In a more preferred embodiment, the alloys herein are substantially free of nickel and copper, meaning that nickel and copper are present only as potential impurities, such as at a level of 0 to 5000 ppm, or 0 to 4000 ppm, or 0 to 3000 ppm, or 0 to 2000 ppm, or 0 to 1000 ppm.

[0045] The alloys herein were processed into a laboratory sheet by processing of laboratory slabs. Laboratory alloy processing is developed to mimic closely the commercial sheet production by continuous casting and include hot rolling and cold rolling. Annealing might be applied depending on targeted properties. Produced sheet can be used in hot rolled (hot band), cold rolled, annealed or partially annealed states.

Laboratory Slab Casting

[0046] Alloys were weighed out into 3,000 to 3,400 gram charges according to the atomic ratios in Table 1 using commercially available ferroadditive powders and a base steel feedstock with known chemistry. Impurities can be present at various levels depending on the feedstock used. Impurity elements would commonly include the following elements; Co, N, P, Ti, Mo, W, Ga, Ge, Sb, Nb, Zr, O, Sn, Ca, B, and S which if present would be in the range from 0 to 5,000 ppm (parts per million) (0 to 0.5 wt %) at the expense of the desired elements noted previously. Preferably, the level of impurities is controlled to fall in the range of 0 to 3,000 ppm (0.3 wt %).

[0047] Charges were loaded into a zirconia coated silica crucible which was placed into an Indutherm VTC800V vacuum tilt casting machine. The machine then evacuated the casting and melting chambers and flushed with argon to atmospheric pressure twice prior to casting to prevent oxidation of the melt. The melt was heated with a 14 kHz RF induction coil until fully molten, approximately from 5 to 7 minutes depending on the alloy composition and charge mass. After the last solids were observed to melt it was allowed to heat for an additional 30 to 45 seconds to provide superheat and ensure melt homogeneity. The casting machine then evacuated the chamber and tilted the crucible and poured the melt into a water-cooled copper die. The melt was allowed to cool under vacuum for 200 seconds before the chamber was filled with argon to atmospheric pressure.

Physical Properties of Cast Alloys

[0048] A sample of between 50 and 150 mg from each alloy herein was taken in the as-cast condition. This sample was heated to an initial ramp temperature between 900° C. and 1300° C. depending on alloy chemistry, at a rate of 40° C./min. Temperature was then increased at 10° C./min to a max temperature between 1425° C. and 1510° C. (maximum temperature limit for the used DSC equipment) depending on alloy chemistry. Once this maximum temperature was achieved, the sample was cooled at a rate of 10° C./min back to the initial ramp temperature before being reheated at 10° C./min to the maximum temperature. Differential Scanning calorimetry (DSC) measurements were taken using a Netzsch Pegasus 404 DSC through all four stages of the experiment, and this data was used to determine the solidus and liquidus temperatures of each alloy, which are in a range from 1325 to 1510° C. as listed in Table 2. Depending on the alloy's chemistry, liquidus-solidus gap varies from 38 to 139° C. Thermal analysis provides information on maximum temperature for the following hot rolling processes that varies depending on alloy chemistry.

TABLE 2

Thermal Analysis Of Selected Alloys			
Alloy	Solidus (° C.)	Liquidus (° C.)	Melting Gap (° C.)
Alloy 1	1346	1455	109
Alloy 2	1423	1472	49

TABLE 2-continued

Thermal Analysis Of Selected Alloys

Alloy	Solidus (° C.)	Liquidus (° C.)	Melting Gap (° C.)
Alloy 3	1430	1486	56
Alloy 4	1409	1471	62
Alloy 5	1374	1460	85
Alloy 6	1364	1475	111
Alloy 7	1347	1466	119
Alloy 8	1325	1463	139
Alloy 9	1355	1475	120
Alloy 10	1340	1471	131
Alloy 11	1352	1464	112
Alloy 12	1385	1470	85
Alloy 13	1342	1459	117
Alloy 14	1391	1481	90
Alloy 15	1423	1506	84
Alloy 16	1377	1469	91
Alloy 17	1353	1473	120
Alloy 18	1408	1481	73
Alloy 19	1341	1450	109
Alloy 20	1390	1491	101
Alloy 21	1424	1510	86
Alloy 22	1367	1475	108
Alloy 23	1366	1464	98
Alloy 24	1367	1459	92
Alloy 25	1368	1463	94
Alloy 26	1402	1476	74
Alloy 27	1397	1474	77
Alloy 28	1403	1481	78
Alloy 29	1389	1479	90
Alloy 30	1377	1479	102
Alloy 31	1378	1466	88
Alloy 32	1377	1454	77
Alloy 33	1420	1478	58
Alloy 34	1400	1452	52
Alloy 35	1439	1482	43
Alloy 36	1426	1464	38
Alloy 37	1411	1502	91
Alloy 38	1392	1445	53
Alloy 39	1390	1451	61
Alloy 40	1386	1452	66

[0049] The density of the alloys herein was measured on samples from hot rolled material using the Archimedes method in a specially constructed balance allowing weighing in both air and distilled water. The density of each alloy is tabulated in Table 3 and was found to be in the range from 7.35 to 7.90 g/cm^3. The accuracy of this technique is ±0.01 g/cm^3.

TABLE 3

Density Of Alloys

Alloy	Density (g/cm^3)
Alloy 1	7.48
Alloy 2	7.69
Alloy 3	7.80
Alloy 4	7.67
Alloy 5	7.55
Alloy 6	7.57
Alloy 7	7.49
Alloy 8	7.35
Alloy 9	7.51
Alloy 10	7.42
Alloy 11	7.52
Alloy 12	7.51
Alloy 13	7.50
Alloy 14	7.61
Alloy 15	7.68
Alloy 16	7.58

TABLE 3-continued

Density Of Alloys

Alloy	Density (g/cm^3)
Alloy 17	7.49
Alloy 18	7.48
Alloy 19	7.47
Alloy 20	7.57
Alloy 21	7.65
Alloy 22	7.38
Alloy 23	7.56
Alloy 24	7.56
Alloy 25	7.56
Alloy 26	7.58
Alloy 27	7.57
Alloy 28	7.58
Alloy 29	7.59
Alloy 30	7.59
Alloy 31	7.59
Alloy 32	7.50
Alloy 33	7.73
Alloy 34	7.82
Alloy 35	7.79
Alloy 36	7.90
Alloy 37	7.60
Alloy 38	7.73
Alloy 39	7.74
Alloy 40	7.76

Laboratory Processing into Hot Band Through Hot Rolling

[0050] The alloys herein were preferably processed into a laboratory hot band by hot rolling of laboratory slabs at high temperatures. Laboratory alloy processing is developed to simulate the hot band production from slabs produced by continuous casting. Industrial hot rolling is performed by heating a slab in a tunnel furnace to a target temperature, then passing it through either a reversing mill or a multi-stand mill or a combination of both to reach the target gauge. During rolling on either mill type, the temperature of the slab is steadily decreasing due to heat loss to the air and to the work rolls, so the final hot band is formed at a reduced temperature. This is simulated in the laboratory by heating in a tunnel furnace to between 1100° C. and 1250° C., then hot rolling. The laboratory mill is slower than industrial mills causing greater loss of heat during each hot rolling pass, so the slab is reheated for 4 minutes between passes to reduce the drop in temperature. The final temperature at target gauge when exiting the laboratory mill commonly is in the range from 800° C. to 1,000° C., depending on furnace temperature and final thickness.

[0051] Prior to hot rolling, laboratory slabs were preheated in a Lucifer EHS3GT-B18 furnace. The furnace set point varies between 1100° C. to 1250° C., depending on alloy melting point and point in the hot rolling process, with the initial temperatures set higher to facilitate higher reductions, and later temperatures set lower to minimize surface oxidation on the hot band. The slabs were allowed to soak for 40 minutes prior to hot rolling to ensure they reach the target temperature and then pushed out of the tunnel furnace into a Fenn Model 061 2 high rolling mill. The 50 mm casts were hot rolled for 5 to 10 passes though the mill before being allowed to air cool. Final thickness ranges after hot rolling are preferably from 1.5 mm to 8.0 mm with variable reduction per pass ranging from 20% to 50%.

[0052] Tensile testing results for hot band with thickness from 1.8 to 2.7 mm are listed in Table 4. Two to four specimens were tested for each alloy. The ultimate tensile strength values of the annealed sheet from alloys herein are in a range from 732 to 1434 MPa, the yield strength at 0.2% offset (a parallel line is drawn on the initial stress strain curve and the resulting point of intersection is measured at the 0.2% offset) varies from 405 to 771 MPa, the total elongation recorded in the range from 17.2 to 69.5%, strength ductility product toughness, i.e. the ultimate tensile strength times the total elongation, varies from 17,500 to 71,100 MPa %, and a Modulus of toughness which is calculated in a range from 152 to 580 N/mm^2. Note that the Modulus of Toughness represents the numerical integration of the stress-strain curve area under tensile stress-strain curve from no applied strain all the way up to failure. The Table 4 properties correspond to Step **2** in FIG. **1**.

TABLE 4

Tensile Properties Of Hot Band Sheet

Alloy	Total Elongation (%)	Ultimate Tensile Strength (MPa)	Yield Strength, 0.2% Offset (MPa)	Strength Ductility Product (MPa %)	Area Under Stress-Strain Curve (N · mm/mm^3)	Thickness (mm)
Alloy 1	66.7	954	575	63,600	570	2.2
	69.5	935	554	65,000	580	2.3
	68.2	936	557	63,800	570	2.3
	68.0	935	556	63,600	569	2.3
Alloy 2	57.2	762	451	45,600	392	2.0
	60.1	749	440	45,000	403	2.0
	57.6	774	466	44,600	403	2.0
	67.6	763	441	51,600	466	2.0
Alloy 3	45.3	833	459	37,700	322	1.9
	50.9	863	488	43,900	379	1.9
	54.4	867	488	47,100	408	1.9
	47.5	860	504	40,900	354	2.0
Alloy 4	66.7	830	524	53,300	504	2.1
	62.4	830	535	51,800	469	2.1
	61.8	827	535	51,100	462	2.1
	59.8	818	520	48,900	440	2.1
Alloy 5	63.5	794	574	50,400	476	2.0
	61.9	791	572	48,900	461	2.0
	58.2	792	555	46,100	431	1.9
	44.9	783	548	35,100	324	1.9
Alloy 6	46.3	1382	431	64,000	478	2.3
	46.0	1383	434	63,600	474	2.3
	38.2	1388	432	53,100	369	2.3
	44.8	1381	434	61,800	454	2.3
Alloy 7	50.1	1315	518	65,800	502	2.2
	48.9	1302	508	63,700	488	2.2
	51.4	1309	497	67,300	518	2.2
	48.6	1305	507	63,500	488	2.2
Alloy 8	27.3	966	771	26,400	253	2.2
	24.0	960	703	23,000	220	2.2
	23.6	960	681	22,700	217	2.2
	31.2	964	717	30,000	289	2.2
Alloy 9	34.9	1434	460	50,100	339	2.2
	27.1	1345	448	36,500	228	2.2
	31.6	1404	468	44,400	290	2.3
	28.7	1411	440	40,400	249	2.2
Alloy 10	46.2	1255	628	57,900	471	2.2
	47.7	1250	608	59,600	478	2.2
	41.7	1223	515	51,000	402	2.7
	42.3	1214	573	51,300	406	2.7
Alloy 11	29.2	1261	505	36,800	245	2.2
	31.4	1299	504	40,800	274	2.2
	35.9	1346	500	48,300	334	2.2
Alloy 12	37.5	1247	429	46,700	349	2.1
	38.4	1244	424	47,700	359	2.1
	37.6	1246	485	46,800	352	2.1
Alloy 13	31.6	1037	662	32,800	275	2.2
	28.8	1007	658	29,000	245	2.1
	34.2	1065	635	36,400	301	2.2
Alloy 14	43.9	1274	494	55,900	410	2.1
	46.9	1242	505	58,300	449	2.1
	46.3	1261	507	58,400	440	2.1
Alloy 15	46.7	1123	478	52,500	406	1.9
	48.2	1112	479	53,600	423	1.9
	45.9	1115	469	51,100	399	1.9
Alloy 16	44.0	1277	411	56,200	417	2.1
	45.2	1296	426	58,600	428	2.1
	41.6	1287	429	53,600	385	2.1

TABLE 4-continued

Tensile Properties Of Hot Band Sheet

Alloy	Total Elongation (%)	Ultimate Tensile Strength (MPa)	Yield Strength, 0.2% Offset (MPa)	Strength Ductility Product (MPa %)	Area Under Stress-Strain Curve (N · mm/mm^3)	Thickness (mm)
Alloy 17	35.6	1385	514	49,300	344	2.1
	35.1	1374	512	48,200	333	2.1
	37.2	1393	523	51,800	366	2.1
Alloy 18	36.8	1264	454	46,500	357	2.2
	37.7	1266	482	47,800	368	2.2
	36.7	1261	484	46,200	354	2.2
Alloy 19	24.7	982	625	24,200	198	2.2
	25.7	1002	624	25,800	209	2.2
	26.7	1023	611	27,300	218	2.2
Alloy 20	41.1	1364	495	56,000	402	2.1
	30.4	1292	478	39,200	269	2.1
	36.6	1351	497	49,400	348	2.1
Alloy 21	42.9	1226	450	52,600	407	2.0
	40.5	1227	450	49,700	378	2.0
	39.8	1233	436	49,000	370	2.0
Alloy 22	17.2	1016	692	17,500	152	2.0
	17.8	1019	760	18,100	157	2.0
Alloy 23	53.0	1236	492	65,500	507	2.1
	36.4	1184	494	43,100	312	2.1
	48.5	1250	513	60,700	457	2.1
Alloy 24	45.0	1247	482	56,200	417	2.0
	49.2	1254	492	61,800	464	2.1
	45.9	1247	482	57,300	427	2.1
Alloy 25	41.5	1260	480	52,300	378	2.1
	34.0	1169	486	39,700	286	2.1
	56.9	1250	482	71,100	567	2.1
Alloy 26	49.1	1276	473	62,600	473	2.1
	50.7	1290	484	65,400	493	2.1
Alloy 27	51.3	1252	451	64,200	495	2.1
	35.6	1230	456	43,800	306	2.0
	46.6	1256	437	58,500	438	2.1
Alloy 28	46.7	1283	414	59,800	444	2.0
	47.3	1271	412	60,200	450	2.0
	48.5	1269	412	61,500	467	2.1
Alloy 29	45.2	1312	446	59,300	441	2.0
	47.2	1310	455	61,800	464	2.0
	45.3	1318	450	59,800	439	2.0
Alloy 30	43.1	1318	428	56,700	410	2.0
	43.8	1338	430	58,600	421	2.0
	37.4	1313	430	49,100	341	2.0
Alloy 31	39.0	1293	408	50,400	355	2.0
	33.5	1271	405	42,500	284	2.0
	40.2	1297	410	52,200	372	2.0
Alloy 32	41.4	951	650	39,300	353	2.1
	42.7	962	650	41,100	365	2.1
	42.6	960	654	40,900	371	2.1
Alloy 33	57.4	829	533	47,600	436	1.9
	62.7	831	543	52,100	480	1.9
	59.4	831	542	49,300	452	1.9
Alloy 34	53.9	855	571	46,100	422	1.8
	57.2	855	586	48,900	452	1.8
	56.2	857	583	48,200	444	1.8
Alloy 35	59.2	826	473	48,900	442	1.8
	60.8	836	486	50,800	460	1.9
	61.2	836	478	51,200	463	1.9
Alloy 36	59.2	736	415	43,600	396	1.8
	59.4	732	408	43,500	395	1.8
	61.8	745	430	46,000	421	1.8
Alloy 37	46.1	970	539	44,700	361	2.0
	38.2	939	539	35,800	292	2.0
	38.8	943	535	36,500	298	2.0
Alloy 38	63.1	844	446	53,300	479	1.9
	66.4	839	457	55,700	503	2.0
	61.5	840	447	51,600	465	2.0
	65.2	851	463	55,400	502	2.0
Alloy 39	64.5	893	455	57,600	513	2.0
	61.2	877	438	53,700	478	2.0
	64.5	875	430	56,400	503	2.0
	61.5	890	428	54,700	486	2.0

TABLE 4-continued

Tensile Properties Of Hot Band Sheet						
Alloy	Total Elongation (%)	Ultimate Tensile Strength (MPa)	Yield Strength, 0.2% Offset (MPa)	Strength Ductility Product (MPa %)	Area Under Stress-Strain Curve (N · mm/mm^3)	Thickness (mm)
Alloy 40	61.4	948	423	58,200	515	1.9
	62.8	945	436	59,300	527	1.9
	62.5	946	440	59,000	525	1.9
	64.2	946	451	60,600	540	1.9

Further Laboratory Processing into Sheet Through Cold Rolling and Annealing

[0053] Alloys with chemistries listed in Table 1 were laboratory cast into ingots with 50 mm thickness. The ingots then were hot rolled at the temperature in a range between 1100° C. and 1250° C. and afterward the hot rolled material (i.e. hot band) was media blasted prior to cold rolling to remove surface oxides which could become embedded during the rolling process. Final thickness after cold rolling are preferably from 0.5 mm to 3.0 mm with variable reduction per pass ranging from 10% to 50%.

[0054] For this specific study, hot rolling was done to produce sheet in a range from 1.9 mm to 2.3 mm which was cold rolled using a Fenn Model 061 2 high rolling mill to a thickness range from 1.1 to 1.4 mm with reductions from 10% to 40%. Once the final gauge thickness was reached, tensile samples were cut from the laboratory sheet by wire-EDM. An example of tensile specimen before testing and its dimensions are shown in FIG. **3**. The samples were annealed under conditions intended to simulate the thermal exposure expected during an industrial continuous annealing process (850° C. for 10 min) or batch annealing (950° C. for 6 hr) representing final treatment of sheet material in Step **2** in FIG. **2**. Samples for 850° C. heat treatment were wrapped in stainless steel foil to prevent oxidation and loaded into a preheated furnace at 850° C. Samples were left in the furnace for 10 minutes while the furnace purged with argon before being removed and allowed to air cool. Samples for 950° C. heat treatment were placed in a hydrogen furnace at room temperature, heated up to 950° C. in hydrogen and argon atmosphere, held for 6 hours, and cooled in the furnace to less than 100° C. in argon.

[0055] Tensile properties were measured on an Instron mechanical testing frame (Model 3369), utilizing Instron's Bluehill control and analysis software. All tests were run at ambient temperature in displacement control at a constant displacement rate of 0.036 mm/s.

[0056] Tensile properties of sheet material with thickness from 1.1 to 1.4 mm from alloys herein after annealing at 850° C. for 10 min are listed in Table 5. The ultimate tensile strength values of the annealed sheet from alloys herein are in a range from 717 to 1414 MPa, the yield strength at 0.2% offset varies from 273 to 838 MPa, the total elongation recorded in the range from 20.8 to 78.9%, strength ductility product toughness varies from 20,500 to 77,100 MPa %, and area under tensile stress-strain curve is calculated in a range from 135 to 677 N/mm^2. Note that the Table 5 properties correspond to Step **2** in FIG. **2**.

TABLE 5

Tensile Properties Of Final Sheet After Annealing At 850° C. For 10 min					
Alloy	Total Elongation (%)	Ultimate Tensile Strength (MPa)	Yield Strength, 0.2% Offset (MPa)	Strength Ductility Product (MPa %)	Area Under Stress-Strain Curve (N · mm/mm^3)
Alloy 1	78.6	887	455	69,700	616
	78.9	888	459	70,000	619
	78.5	880	455	69,100	613
	77.7	890	467	69,100	614
Alloy 2	76.4	762	355	58,200	509
	73.1	756	350	55,200	481
	76.4	761	356	58,100	511
	72.0	755	352	54,400	475
Alloy 3	67.4	838	339	56,500	470
	65.3	825	333	53,800	446
	62.3	830	336	51,700	427
	62.9	815	333	51,200	423
Alloy 4	65.3	773	366	50,400	432
	71.8	778	359	55,800	481
	72.0	774	361	55,700	483
	68.5	774	363	53,000	458
Alloy 5	72.9	755	394	55,000	492
	69.9	757	392	52,900	474
	69.3	752	389	52,100	463
	67.9	752	395	69,700	454
Alloy 6	40.5	1390	522	56,200	399
	39.7	1393	518	55,300	390
	42.6	1396	534	59,400	429
Alloy 7	55.2	1243	609	68,600	543
	56.0	1274	604	71,200	554
Alloy 8	47.2	951	660	44,900	423
	42.5	966	626	41,100	386
	46.9	954	637	44,700	422
	41.1	965	644	39,700	372
Alloy 9	43.6	1407	623	61,100	453
	43.7	1414	639	61,600	454
Alloy 10	57.6	1120	615	64,400	563
	58.8	1124	668	66,000	577
	57.4	1121	651	64,300	560
Alloy 11	48.1	1354	563	65,100	476
	46.6	1338	568	62,400	455
	49.7	1333	560	66,200	493
Alloy 12	38.0	1251	613	47,600	361
	37.4	1253	599	46,800	354
	38.0	1251	610	47,600	362
Alloy 13	38.6	1052	581	40,600	328
	44.7	1095	573	48,900	388
	42.2	1085	574	45,800	366
Alloy 14	48.4	1219	401	59,000	425
	47.3	1226	409	57,900	417
	51.6	1208	408	62,300	468
Alloy 15	51.6	1052	317	54,300	406
	50.4	1087	320	54,800	394
	55.4	1053	321	58,400	446
Alloy 16	42.3	1317	477	55,700	387
	42.6	1310	481	55,800	394

TABLE 5-continued

Tensile Properties Of Final Sheet After Annealing At 850° C. For 10 min

Alloy	Total Elongation (%)	Ultimate Tensile Strength (MPa)	Yield Strength, 0.2% Offset (MPa)	Strength Ductility Product (MPa %)	Area Under Stress-Strain Curve (N · mm/mm³)
	48.5	1301	482	63,100	467
	46.9	1307	474	61,300	447
Alloy 17	49.0	1331	663	65,200	504
	53.1	1330	663	70,600	560
	52.4	1325	649	69,500	550
Alloy 18	39.2	1232	648	48,300	383
	38.5	1234	669	47,500	375
	37.5	1229	644	46,100	363
Alloy 19	43.9	1205	619	52,900	409
	52.0	1271	621	66,100	511
	59.2	1302	616	77,100	604
Alloy 20	20.8	982	435	20,500	135
	22.9	1078	463	24,700	160
	23.0	1103	466	25,300	162
Alloy 21	26.8	1070	343	28,700	187
	22.7	1017	342	23,100	151
	30.5	1139	349	34,700	235
Alloy 22	37.8	1055	768	39,900	373
	39.9	1036	838	41,300	386
	36.3	1038	745	37,600	349
Alloy 23	56.1	1225	463	68,800	518
	56.5	1214	462	68,600	518
	56.2	1219	470	68,400	519
Alloy 24	56.9	1244	473	70,800	531
	53.5	1229	470	65,700	491
	53.1	1241	465	65,900	484
Alloy 25	47.4	1249	474	59,100	421
	57.3	1236	470	70,800	542
	52.0	1241	474	64,500	483
Alloy 26	48.4	1288	451	62,300	445
	50.3	1270	463	63,900	471
	50.2	1285	461	64,500	469
Alloy 27	45.1	1304	455	58,800	406
	51.1	1287	472	65,700	481
	46.0	1282	460	59,000	422
Alloy 28	45.2	1301	460	58,700	418
	43.3	1279	439	55,400	390
	46.6	1279	457	59,600	435
Alloy 29	44.9	1326	439	59,500	415
	43.6	1321	443	57,500	402
	49.5	1315	442	65,100	477
Alloy 30	46.0	1348	445	62,100	434
	45.2	1345	436	60,800	427
	44.8	1330	444	59,600	421
Alloy 31	45.5	1324	443	60,200	516
	44.6	1367	448	61,000	517
	44.8	1346	439	60,200	508
Alloy 32	67.1	1027	551	68,900	606
	73.2	1048	571	76,700	677
	66.6	1051	574	70,000	611
Alloy 33	68.7	819	367	56,300	489
	68.2	823	371	56,100	488
	69.1	829	374	57,200	499
Alloy 34	50.3	918	478	46,200	414
	53.4	918	477	49,000	441
	53.1	899	449	47,700	423
Alloy 35	75.4	795	287	60,000	508
	66.3	784	292	52,000	437
	75.8	798	293	60,500	513
Alloy 36	74.2	717	273	53,200	463
	71.9	727	282	52,300	454
	71.4	739	282	52,800	456
Alloy 37	57.5	1041	368	59,900	460
	53.9	1048	372	56,500	430
	56.7	1020	365	57,800	452
Alloy 38	71.7	845	379	60,500	530
	73.3	846	373	61,900	542
	70.7	853	389	60,200	528
	68.2	850	381	58,000	505
Alloy 39	69.9	894	390	62,400	537
	69.1	903	388	62,400	534
	71.7	904	394	64,800	557
	70.4	883	376	62,000	534
Alloy 40	70.3	971	402	68,200	576
	71.9	956	408	68,600	588
	68.6	956	403	65,500	557
	71.1	935	391	66,500	569

[0057] Tensile properties of sheet material with thickness from 1.1 to 1.4 mm from alloys herein after annealing at 950° C. for 6 hr are listed in Table 6. The ultimate tensile strength values of the annealed sheet from alloys herein are in a range from 679 to 1418 MPa, the yield strength at 0.2% offset varies from 209 to 588 MPa, the total elongation recorded in the range from 12.0 to 88.2%, strength ductility product toughness varies from 11,000 to 76,200 MPa %, and area under tensile stress-strain curve is calculated in a range from 101 to 663 N/mm^2. Note that the Table 6 properties correspond to Step **2** in FIG. **2**.

TABLE 6

Tensile Properties of Final Sheet After Annealing At 950° C. For 6 Hr

Alloy	Total Elongation (%)	Ultimate Tensile Strength (MPa)	Yield Strength, 0.2% Offset (MPa)	Strength Ductility Product (MPa %)	Area Under Stress-Strain Curve (N · mm/mm³)
Alloy 1	84.6	849	328	71,800	594
	81.6	850	330	69,300	572
	85.8	828	322	71,100	591
	84.5	845	328	71,400	591
Alloy 2	88.2	687	281	60,600	526
	80.8	684	281	55,300	473
	86.6	688	283	59,600	514
	81.8	683	280	55,800	475
Alloy 3	76.2	747	275	56,900	460
	75.8	751	275	56,900	456
	74.7	753	273	56,200	455
	85.9	758	278	65,100	536
Alloy 4	75.6	696	287	52,600	443
	82.4	703	291	57,900	495
	83.7	699	288	58,500	498
	83.9	705	288	59,100	507
Alloy 5	81.6	681	305	55,500	489
	82.6	679	302	56,100	495
	78.2	684	308	53,500	473
	78.7	682	305	53,700	473
Alloy 6	27.1	1247	334	33,600	191
	31.8	1328	340	42,300	254
	42.4	1353	342	57,300	391
	34.5	1332	338	45,800	285
Alloy 7	46.5	1304	355	60,600	417
	43.4	1304	357	56,600	378
	41.0	1301	358	53,300	347
	47.1	1304	361	61,400	428
Alloy 8	38.9	919	467	35,800	330
	47.1	923	474	43,400	406

TABLE 6-continued

Tensile Properties of Final Sheet After Annealing At 950° C. For 6 Hr

Alloy	Total Elongation (%)	Ultimate Tensile Strength (MPa)	Yield Strength, 0.2% Offset (MPa)	Strength Ductility Product (MPa %)	Area Under Stress-Strain Curve (N · mm/mm^3)
	53.7	925	447	49,600	466
	42.2	923	456	38,900	360
Alloy 9	34.6	1418	356	49,000	308
	29.8	1379	354	41,000	238
	28.1	1340	346	37,500	213
	27.2	1332	346	36,100	203
Alloy 10	31.8	1083	427	34,400	257
	31.2	1081	433	33,700	252
	32.4	1104	427	35,700	266
Alloy 11	39.1	1327	356	51,900	328
	33.6	1266	354	42,600	252
	33.7	1270	357	42,800	254
Alloy 12	32.7	1236	319	40,400	289
	33.0	1236	319	40,800	292
	33.2	1240	318	41,100	294
Alloy 13	45.9	952	396	43,700	326
	46.0	954	396	43,800	326
Alloy 14	41.9	1242	299	52,100	333
	41.7	1236	303	51,500	331
	47.7	1232	301	58,800	406
Alloy 15	46.7	1065	240	49,700	332
	40.7	1069	240	43,500	271
	44.8	1083	241	48,500	324
Alloy 16	41.3	1256	328	51,800	340
	41.6	1261	310	52,500	346
	44.9	1256	321	56,400	386
	48.6	1250	321	60,700	432
Alloy 17	42.7	1404	377	59,900	410
	42.9	1401	377	60,100	414
	43.4	1401	377	60,800	420
Alloy 18	32.9	1264	380	41,600	310
	32.4	1257	370	40,700	303
	32.2	1260	370	40,600	302
Alloy 19	43.9	1078	405	47,300	327
	40.3	1030	405	41,500	291
	40.6	1041	406	42,300	295
Alloy 20	40.3	1273	300	51,300	344
	39.2	1275	299	50,000	335
	40.7	1300	301	52,900	354
Alloy 21	39.4	1202	240	47,300	331
	39.1	1196	241	46,800	325
	36.8	1201	242	44,200	302
Alloy 22	13.8	930	563	12,800	117
	15.1	940	588	14,200	129
	12.0	916	556	11,000	101
Alloy 23	52.2	1195	333	62,300	429
	56.9	1192	334	67,800	487
	49.8	1201	332	59,800	404
Alloy 24	53.9	1179	338	63,500	448
	51.1	1189	329	60,700	421
	55.0	1193	330	65,700	467
Alloy 25	38.7	1142	326	44,200	278
	55.5	1203	326	66,700	473
	55.1	1198	329	66,000	470
Alloy 26	42.4	1244	318	52,700	334
	37.9	1210	322	45,800	281
	49.1	1233	320	60,600	418
Alloy 27	50.7	1234	315	62,600	436
	50.5	1237	326	62,400	440
	47.2	1233	316	58,100	397
Alloy 28	44.9	1232	302	55,400	376
	46.1	1248	315	57,500	393
	38.1	1228	301	46,800	296
Alloy 29	39.8	1297	310	51,700	321
	45.3	1269	321	57,400	389
	42.2	1279	321	53,900	348
Alloy 30	44.8	1279	321	57,300	384
	46.3	1297	321	60,100	403
	44.4	1298	318	57,600	378

TABLE 6-continued

Tensile Properties of Final Sheet After Annealing At 950° C. For 6 Hr

Alloy	Total Elongation (%)	Ultimate Tensile Strength (MPa)	Yield Strength, 0.2% Offset (MPa)	Strength Ductility Product (MPa %)	Area Under Stress-Strain Curve (N · mm/mm^3)
Alloy 31	47.5	1311	323	62,200	419
	41.7	1268	317	52,800	343
	42.0	1284	324	54,000	349
Alloy 32	87.4	868	406	75,800	659
	84.9	869	407	73,700	638
	88.1	865	406	76,200	663
Alloy 33	79.2	716	260	56,700	474
	83.1	716	261	59,500	502
	83.1	716	261	59,500	501
Alloy 34	73.0	775	296	56,500	481
	67.9	788	307	53,600	456
	69.2	776	302	53,700	456
Alloy 35	84.9	712	226	60,400	501
	79.0	699	225	55,200	454
	81.0	697	227	56,400	464
Alloy 36	76.6	725	209	55,500	456
	77.8	717	212	55,800	461
	77.1	718	209	55,400	455
Alloy 37	36.4	736	238	26,800	176
	29.2	693	239	20,200	135
	29.9	706	238	21,100	140
Alloy 38	81.3	791	289	64,300	546
	77.8	792	291	61,600	520
	78.0	779	287	60,800	515
Alloy 39	78.3	868	294	67,900	556
	79.2	861	292	68,200	559
	79.0	866	294	68,300	560
Alloy 40	77.1	959	290	73,900	593
	74.7	947	292	70,700	569
	74.7	955	290	71,400	575

Toughness Testing

[0058] Materials toughness was measured by Charpy V-notch testing and bulk fracture testing. Charpy V-notch and bulk fracture samples were machined by wire EDM from cold rolled sheet. Charpy V-notch samples are machined in an L-T orientation (sample length in rolling direction, notch in transverse direction), while bulk fracture samples are machined in L-N orientation (length in rolling direction, striking direction is normal to rolled surface). The samples were then annealed either at 850° C. for 10 minutes in argon/air atmosphere or at 950° C. for 6 hours in hydrogen atmosphere.

[0059] The geometry of Charpy V-notch samples were cut in accordance with ASTM E23-12c (10 mm×55 mm×thickness with a centered 45° V-notch of 0.25 mm radius, 2 mm in depth with a surface finish Ra of less than 2.0 μm on notch and strike face). An example of the Charpy V-notch specimen before testing and its schematic illustration are shown in FIG. **4**. Charpy V-notch samples are mounted using self-centering tongs to ensure the samples are centered on the anvil. Testing was done by using the Instron SI-1B Pendulum Impact Tester. The arm of the Impact Tester is set to the high latch position with 26.6 lb weights configured for indicating dial maximum reading of 120 ft-lb (162.7 J). The latch is released and the reading of energy absorbed by the sample is recorded in ft-lb and then converted to joules. The grips of bulk fracture Charpy samples are placed in a cutout in the anvil and a screw is tightened down on the grips to constrain the sample in the anvil.

[0060] Testing results are shown in Table 7. Absorbed energy values during Charpy V-notch testing of alloys herein are in a range from 0.7 to 26.1 J in cold rolled and annealed sheet with thickness from 1.1 to 1.4 mm. Thickness normalized values of the Charpy V-notched toughness vary from 0.5 to 21.8 J/mm. Note that the Table 7 properties correspond to Step **2** in FIG. **2**.

TABLE 7

Charpy V-Notch Testing Data (1.1 to 1.4 mm Thickness)

Alloy	Annealing	V-Notch Charpy Toughness (J)			Thickness (mm)	Thickness Normalized V-Notch Charpy Toughness (J/mm)		
Alloy 1	850° C. 10 min	10.8	10.5	11.2	1.2	9.0	8.8	9.3
	950° C. 6 hr	16.3	18.3	19.0	1.2	13.6	15.3	15.8
Alloy 2	850° C. 10 min	16.3	13.2	13.6	1.2	13.6	11.0	11.3
	950° C. 6 hr	15.6	15.6	12.2	1.2	13.0	13.0	10.2
Alloy 3	850° C. 10 min	13.6	14.2	16.3	1.2	11.3	11.8	13.6
	950° C. 6 hr	20.7	16.9	15.9	1.2	17.3	14.1	13.3
Alloy 4	850° C. 10 min	14.2	14.9	14.2	1.2	11.8	12.4	11.8
	950° C. 6 hr	20.7	13.2	19.0	1.2	17.3	11.0	15.8
Alloy 5	850° C. 10 min	14.2	15.6	14.9	1.3	10.9	12.0	11.5
	950° C. 6 hr	19.3	19.3	17.3	1.3	14.8	14.8	13.3
Alloy 6	850° C. 10 min	13.6	13.9	12.9	1.2	11.3	11.6	10.8
	950° C. 6 hr	20.3	20.0	15.6	1.2	16.9	16.7	13.0
Alloy 7	850° C. 10 min	11.2	12.2	12.2	1.2	9.3	10.2	10.2
	950° C. 6 hr	16.9	18.3	16.3	1.2	14.1	15.3	13.6
Alloy 8	850° C. 10 min	6.1	4.7	6.8	1.2	5.1	3.9	5.7
	950° C. 6 hr	1.7	1.7	1.7	1.2	1.4	1.4	1.4
Alloy 9	850° C. 10 min	13.9	12.9	13.6	1.3	10.7	9.9	10.5
	950° C. 6 hr	16.9	17.3	19.0	1.3	13.0	13.3	14.6
Alloy 10	850° C. 10 min	9.5	9.5	10.2	1.2	7.9	7.9	8.5
	950° C. 6 hr	7.8	7.8	7.1	1.2	6.5	6.5	5.9
Alloy 11	850° C. 10 min	12.5	12.9	13.2	1.2	10.4	10.8	11.0
	950° C. 6 hr	18.3	14.9	16.9	1.2	15.3	12.4	14.1
Alloy 12	850° C. 10 min	12.5	11.5	13.6	1.2	10.4	9.6	11.3
	950° C. 6 hr	13.9	15.3	13.6	1.2	11.6	12.8	11.3
Alloy 13	850° C. 10 min	10.2	9.5	9.2	1.2	8.5	7.9	7.7
	950° C. 6 hr	13.6	15.6	14.6	1.2	11.3	13.0	12.2
Alloy 14	850° C. 10 min	13.6	14.2	13.2	1.2	11.3	11.8	11.0
	950° C. 6 hr	17.6	16.6	18.6	1.2	14.7	13.8	15.5
Alloy 15	850° C. 10 min	12.9	12.9	14.9	1.2	10.8	10.8	12.4
	950° C. 6 hr	12.9	18.6	14.6	1.2	10.8	15.5	12.2
Alloy 16	850° C. 10 min	16.3	14.9	14.2	1.2	13.6	12.4	11.8
	950° C. 6 hr	15.3	19.7	19.0	1.2	12.8	16.4	15.8
Alloy 17	850° C. 10 min	14.2	12.9	13.2	1.4	10.1	9.2	9.4
	950° C. 6 hr	19.0	18.3	19.0	1.4	13.6	13.1	13.6
Alloy 18	850° C. 10 min	12.2	12.2	10.5	1.2	10.2	10.2	8.8
	950° C. 6 hr	16.9	18.0	16.3	1.2	14.1	15.0	13.6
Alloy 19	850° C. 10 min	9.8	9.8	9.5	1.4	7.0	7.0	6.8
	950° C. 6 hr	17.3	17.3	16.3	1.4	12.4	12.4	11.6
Alloy 20	850° C. 10 min	13.9	14.6	15.3	1.2	11.6	12.2	12.8
	950° C. 6 hr	19.0	19.0	16.9	1.3	14.6	14.6	13.0
Alloy 21	850° C. 10 min	14.6	15.3	14.2	1.2	12.2	12.8	11.8
	950° C. 6 hr	12.5	16.9	17.6	1.2	10.4	14.1	14.7
Alloy 22	850° C. 10 min	1.4	1.4	1.4	1.4	1.0	1.0	1.0
	950° C. 6 hr	0.7	0.7	0.7	1.4	0.5	0.5	0.5
Alloy 23	850° C. 10 min	14.9	15.6	12.9	1.2	12.4	13.0	10.8
	950° C. 6 hr	14.9	16.9	16.9	1.2	12.4	14.1	14.1
Alloy 24	850° C. 10 min	14.2	15.9	16.9	1.1	12.9	14.5	15.4
	950° C. 6 hr	26.1	16.3	17.6	1.2	21.8	13.6	14.7
Alloy 25	850° C. 10 min	12.5	13.9	12.9	1.2	10.4	11.6	10.8
	950° C. 6 hr	17.6	19.0	16.9	1.2	14.7	15.8	14.1
Alloy 26	850° C. 10 min	13.6	14.9	14.2	1.2	11.3	12.4	11.8
	950° C. 6 hr	15.3	17.3	17.6	1.2	12.8	14.4	14.7
Alloy 27	850° C. 10 min	13.6	14.2	13.6	1.2	11.3	11.8	11.3
	950° C. 6 hr	14.9	16.9	16.3	1.2	12.4	14.1	13.6
Alloy 28	850° C. 10 min	14.6	14.6	14.9	1.2	12.2	12.2	12.4
	950° C. 6 hr	18.6	14.9	14.2	1.2	15.5	12.4	11.8
Alloy 29	850° C. 10 min	14.9	14.9	15.6	1.2	12.4	12.4	13.0
	950° C. 6 hr	16.3	14.8	18.0	1.2	13.6	12.3	15.0
Alloy 30	850° C. 10 min	14.9	14.9	16.3	1.2	12.4	12.4	13.6
	950° C. 6 hr	19.3	17.3	14.9	1.2	16.1	14.4	12.4
Alloy 31	850° C. 10 min	13.6	16.3	14.9	1.2	11.3	13.6	12.4
	950° C. 6 hr	15.6	16.3	14.9	1.2	13.0	13.6	12.4

TABLE 7-continued

Charpy V-Notch Testing Data (1.1 to 1.4 mm Thickness)

Alloy	Annealing	V-Notch Charpy Toughness (J)			Thickness (mm)	Thickness Normalized V-Notch Charpy Toughness (J/mm)		
Alloy 32	850° C. 10 min	8.1	8.5	8.1	1.2	6.8	7.1	6.8
	950° C. 6 hr	16.3	17.3	16.3	1.2	13.6	14.4	13.6
Alloy 33	850° C. 10 min	10.2	10.5	8.5	1.2	8.5	8.8	7.1
	950° C. 6 hr	13.9	14.2	13.6	1.2	11.6	11.8	11.3
Alloy 34	850° C. 10 min	5.4	5.4	5.4	1.2	4.5	4.5	4.5
	950° C. 6 hr	10.8	10.8	11.2	1.2	9.0	9.0	9.3
Alloy 35	850° C. 10 min	13.2	12.9	13.6	1.2	11.0	10.8	11.3
	950° C. 6 hr	13.9	15.3	13.2	1.2	11.6	12.8	11.0
Alloy 36	850° C. 10 min	9.5	11.2	9.5	1.2	7.9	9.3	7.9
	950° C. 6 hr	13.2	11.5	13.9	1.2	11.0	9.6	11.6
Alloy 37	850° C. 10 min	12.5	11.9	12.5	1.2	10.4	9.9	10.4
	950° C. 6 hr	11.5	15.3	13.6	1.2	9.6	12.8	11.3
Alloy 38	850° C. 10 min	11.6	10.2	9.9	1.2	9.4	8.2	8.1
	950° C. 6 hr	14.0	13.3	13.5	1.2	11.7	11.5	10.9
Alloy 39	850° C. 10 min	13.3	11.3	12.1	1.2	10.9	9.3	9.9
	950° C. 6 hr	13.5	13.3	15.5	1.2	11.8	11.1	13.2
Alloy 40	850° C. 10 min	11.3	11.6	10.5	1.2	9.5	10.0	8.8
	950° C. 6 hr	13.8	12.4	11.6	1.2	11.9	11.0	9.7

[0061] Bulk fracture samples have 45 mm long by 2 mm wide parallel region between two wedge shaped grips designed to be clamped into a cutout in the anvil. An example of the specimen before testing and its schematic illustration are shown in FIG. **5**. The grips of bulk fracture samples are placed in a cutout in the anvil of the Instron SI-1B Pendulum Impact Tester and a screw is tightened down on the grips to constrain the sample in the anvil. The arm of the Impact Tester is set to the high latch position with 26.6 lb weights configured for indicating dial maximum reading of 120 ft-lb (162.7 J). The latch is released and the reading of energy absorbed by the sample is recorded. That value is converted to joules.

[0062] Testing results are shown in Table 8. Absorbed energy values during bulk fracture testing of alloys herein are in a range from 5.8 to 75.2 J for the cold rolled and annealed sheet with thickness of 1.1 to 1.4 mm. Thickness normalized values of bulk fracture toughness vary from 4.1 to 53.7 J/mm. Note that the Table 8 properties correspond to Step **2** in FIG. **2**.

TABLE 8

Bulk Fracture Testing Data (1.1 to 1.4 mm Thickness)

Alloy	Annealing	Bulk Fracture Toughness (J)			Thickness (mm)	Thickness Normalized Bulk Fracture Toughness (J/mm)		
Alloy 1	850° C. 10 min	41.7	43.4	43.7	1.2	34.8	36.2	36.4
	950° C. 6 hr	54.6	53.2	52.9	1.2	45.5	44.3	44.1
Alloy 2	850° C. 10 min	33.6	34.6	35.6	1.1	30.5	31.5	32.4
	950° C. 6 hr	44.1	43.0	44.1	1.1	40.1	39.1	40.1
Alloy 3	850° C. 10 min	42.7	43.0	42.7	1.2	35.6	35.8	35.6
	950° C. 6 hr	47.5	50.8	52.2	1.2	39.6	42.3	43.5
Alloy 4	850° C. 10 min	38.0	37.3	38.0	1.2	31.7	31.1	31.7
	950° C. 6 hr	49.1	48.1	47.5	1.2	40.9	40.1	39.6
Alloy 5	850° C. 10 min	38.0	37.6	36.6	1.3	29.2	28.9	28.2
	950° C. 6 hr	42.7	44.1	45.1	1.3	32.8	33.9	34.7
Alloy 6	850° C. 10 min	50.2	51.9	52.2	1.2	41.8	43.3	43.5
	950° C. 6 hr	50.2	51.2	51.9	1.2	41.8	42.7	43.3
Alloy 7	850° C. 10 min	53.2	54.2	54.2	1.2	44.3	45.2	45.2
	950° C. 6 hr	54.9	55.9	51.9	1.2	45.8	46.6	43.3
Alloy 8	850° C. 10 min	25.8	27.1	27.5	1.2	21.5	22.6	22.9
	950° C. 6 hr	19.7	19.3	20.0	1.2	16.4	16.1	16.7
Alloy 9	850° C. 10 min	59.0	59.3	57.6	1.3	45.4	45.6	44.3
	950° C. 6 hr	53.6	59.0	60.0	1.3	41.2	45.4	46.2
Alloy 10	850° C. 10 min	31.9	30.5	33.9	1.2	26.6	25.4	28.3
	950° C. 6 hr	54.9	56.3	55.9	1.2	45.8	46.9	46.6
Alloy 11	850° C. 10 min	55.6	53.6	55.6	1.2	46.3	44.7	46.3
	950° C. 6 hr	54.2	56.3	57.6	1.2	45.2	46.9	48.0
Alloy 12	850° C. 10 min	45.8	44.7	45.4	1.2	38.2	37.3	37.8
	950° C. 6 hr	46.1	45.4	44.7	1.2	38.4	37.8	37.3
Alloy 13	850° C. 10 min	54.9	54.2	55.9	1.2	45.8	45.2	46.6
	950° C. 6 hr	59.7	62.4	63.7	1.2	49.8	52.0	53.1

TABLE 8-continued

Bulk Fracture Testing Data (1.1 to 1.4 mm Thickness)

Alloy	Annealing	Bulk Fracture Toughness (J)			Thickness (mm)	Thickness Normalized Bulk Fracture Toughness (J/mm)		
Alloy 14	850° C. 10 min	50.8	49.1	49.5	1.2	42.3	40.9	41.3
	950° C. 6 hr	51.9	52.2	52.9	1.2	43.3	43.5	44.1
Alloy 15	850° C. 10 min	49.1	50.8	48.8	1.2	40.9	42.3	40.7
	950° C. 6 hr	55.6	54.9	55.6	1.2	46.3	45.8	46.3
Alloy 16	850° C. 10 min	59.0	53.9	54.2	1.2	49.2	44.9	45.2
	950° C. 6 hr	50.8	54.9	56.3	1.2	42.3	45.8	46.9
Alloy 17	850° C. 10 min	67.1	61.0	61.7	1.4	47.9	43.6	44.1
	950° C. 6 hr	64.4	61.0	61.7	1.4	46.0	43.6	44.1
Alloy 18	850° C. 10 min	44.7	43.4	43.4	1.2	37.3	36.2	36.2
	950° C. 6 hr	46.8	45.4	43.4	1.2	39.0	37.8	36.2
Alloy 19	850° C. 10 min	59.7	60.3	60.3	1.4	42.6	43.1	43.1
	950° C. 6 hr	73.2	75.2	71.9	1.4	52.3	53.7	51.4
Alloy 20	850° C. 10 min	50.8	50.2	48.4	1.2	42.3	41.8	40.3
	950° C. 6 hr	53.9	52.2	54.9	1.2	44.9	43.5	45.8
Alloy 21	850° C. 10 min	46.1	43.4	44.7	1.2	38.4	36.2	37.3
	950° C. 6 hr	48.1	49.5	50.2	1.2	40.1	41.3	41.8
Alloy 22	850° C. 10 min	27.8	27.1	28.5	1.4	19.9	19.4	20.4
	950° C. 6 hr	5.8	6.8	8.5	1.4	4.1	4.9	6.1
Alloy 23	850° C. 10 min	50.8	52.5	55.9	1.2	42.3	43.8	46.6
	950° C. 6 hr	53.6	52.2	52.2	1.2	44.7	43.5	43.5
Alloy 24	850° C. 10 min	51.2	52.2	52.9	1.2	42.7	43.5	44.1
	950° C. 6 hr	55.6	56.6	55.6	1.2	46.3	47.2	46.3
Alloy 25	850° C. 10 min	55.6	54.2	52.5	1.2	46.3	45.2	43.8
	950° C. 6 hr	55.6	55.6	56.3	1.2	46.3	46.3	46.9
Alloy 26	850° C. 10 min	52.2	51.5	50.8	1.2	43.5	42.9	42.3
	950° C. 6 hr	54.2	53.6	52.2	1.2	45.2	44.7	43.5
Alloy 27	850° C. 10 min	51.5	50.2	50.2	1.2	42.9	41.8	41.8
	950° C. 6 hr	54.2	52.9	55.6	1.2	45.2	44.1	46.3
Alloy 28	850° C. 10 min	48.8	48.1	50.8	1.2	40.7	40.1	42.3
	950° C. 6 hr	54.9	49.5	52.2	1.2	45.8	41.3	43.5
Alloy 29	850° C. 10 min	54.2	54.2	57.6	1.2	45.2	45.2	48.0
	950° C. 6 hr	56.6	52.5	54.6	1.2	47.2	43.8	45.5
Alloy 30	850° C. 10 min	51.5	52.2	52.2	1.2	42.9	43.5	43.5
	950° C. 6 hr	56.9	55.6	54.6	1.2	47.4	46.3	45.5
Alloy 31	850° C. 10 min	49.5	50.2	49.5	1.2	41.3	41.8	41.3
	950° C. 6 hr	55.6	51.9	55.6	1.2	46.3	43.3	46.3
Alloy 32	850° C. 10 min	43.0	44.7	43.4	1.2	35.8	37.3	36.2
	950° C. 6 hr	54.2	53.6	54.2	1.2	45.2	44.7	45.2
Alloy 33	850° C. 10 min	40.7	37.6	41.0	1.2	33.9	31.3	34.2
	950° C. 6 hr	50.2	48.8	50.2	1.2	41.8	40.7	41.8
Alloy 34	850° C. 10 min	35.9	33.2	35.3	1.2	29.9	27.7	29.4
	950° C. 6 hr	49.5	50.8	47.5	1.2	41.3	42.3	39.6
Alloy 35	850° C. 10 min	43.7	44.1	42.4	1.2	36.4	36.8	35.3
	950° C. 6 hr	49.5	46.8	50.2	1.2	41.3	39.0	41.8
Alloy 36	850° C. 10 min	42.0	40.3	42.0	1.2	35.0	33.6	35.0
	950° C. 6 hr	47.1	43.7	43.4	1.2	39.3	36.4	36.2
Alloy 37	850° C. 10 min	58.0	54.6	56.3	1.2	48.3	45.5	46.9
	950° C. 6 hr	58.3	61.0	57.6	1.2	48.6	50.8	48.0
Alloy 38	850° C. 10 min	38.0	37.9	38.5	1.21	31.2	31.0	32.3
	950° C. 6 hr	40.7	38.8	38.8	1.20	33.7	32.0	32.6
Alloy 39	850° C. 10 min	38.2	38.5	38.5	1.19	31.6	32.2	33.0
	950° C. 6 hr	41.6	41.3	42.9	1.20	34.8	35.1	35.3
Alloy 40	850° C. 10 min	37.3	40.4	38.8	1.18	32.4	33.6	32.4
	950° C. 6 hr	38.3	40.8	39.4	1.19	32.7	34.4	32.9

Case Examples

Case Example #1 Unbroken Samples During Charpy V-Notch Testing

[0063] Charpy V-notch specimens (FIG. **4***b*) were cut out by wire EDM from sheet material with thickness of 1.2 mm from alloys listed in Table 9. The specimens were tested in accordance with Charpy impact testing methodology described in the Main Body of this application. Three specimens were tested for each condition from each alloy and several specimens did not break during the testing as listed in Table 9. Examples of unbroken sample after testing are shown in FIG. **6**. Note that specimens are expected to fail at the stress concentration site due to the presence of the V-notch, unbroken samples were not anticipated that indicates high toughness.

TABLE 9

A Summary Of Unbroken Charpy V-Notch Specimens

Alloy	Condition	Count of Unbroken Samples
Alloy 1	950° C. 6 hr	2
Alloy 2	850° C. 10 min	3
Alloy 2	950° C. 6 hr	3
Alloy 3	850° C. 10 min	3
Alloy 3	950° C. 6 hr	3
Alloy 4	850° C. 10 min	2
Alloy 4	950° C. 6 hr	3
Alloy 5	850° C. 10 min	3
Alloy 5	950° C. 6 hr	1
Alloy 6	950° C. 6 hr	2
Alloy 7	950° C. 6 hr	1
Alloy 11	950° C. 6 hr	2
Alloy 12	950° C. 6 hr	3
Alloy 13	850° C. 6h	3
Alloy 14	950° C. 6 hr	2
Alloy 15	950° C. 6 hr	3
Alloy 15	850° C. 10 min	1
Alloy 18	950° C. 6 hr	1
Alloy 20	950° C. 6 hr	2
Alloy 21	950° C. 6 hr	3

[0064] This Case Example demonstrates that alloys herein show high toughness with a resistance to failure even in the presence of a notch.

Case Example #2 Fractography of Charpy V-Notch Specimens after Testing

[0065] Specimens from Alloy 7, Alloy 9, Alloy 19, and Alloy 20 after Charpy V-notch testing in cold rolled and annealed (850° C. for 10 min) state described in the Main Body section of this application were used for SEM analysis of the fracture surface. The Charpy V-notch testing results for these specific specimens from selected alloys are listed in Table 10. Fractured specimens from each alloy were mounted and analyzed by using a Zeiss MA-10 Scanning Electron Microscope (SEM). Micrographs of the fracture surface in tested specimens are shown in FIG. **7** through FIG. **10** for Alloy 7, Alloy 9, Alloy 19, and Alloy 20, respectively. Cup and cone features typical for a ductile fracture were observed in all analyzed specimens.

TABLE 10

Charpy V-Notch Toughness For Analyzed Specimens

Alloy	Charpy V-Notch Toughness (J)
Alloy 7	12.2
Alloy 9	12.9
Alloy 19	9.8
Alloy 20	15.3

[0066] This Case Example demonstrates that alloys herein undergo a ductile fracture during V-notch impact testing.

Case Example #3 Fractography of Bulk Fracture Specimens after Testing

[0067] Specimens from Alloy 7, Alloy 9, Alloy 19, and Alloy 20 after bulk fracture testing in cold rolled and annealed (850° C. for 10 min) state described in the Main Body section of this application were used for SEM analysis of the fracture surface. The bulk fracture testing results for these specific specimens from selected alloys are listed in Table 11. Fractured specimens from each alloy were mounted and analyzed by using a Zeiss MA-10 Scanning Electron Microscope (SEM). Micrographs of the fracture surface are shown in FIG. **11** through FIG. **14** for Alloy 7, Alloy 9, Alloy 19, and Alloy 20, respectively. Cup and cone features typical for a ductile fracture were observed in all analyzed specimens.

TABLE 11

Bulk Fracture Results

Alloy	Bulk Fracture Toughness (J)
Alloy 7	54.2
Alloy 9	59.3
Alloy 19	60.3
Alloy 20	50.8

[0068] This Case Example demonstrates that alloys herein undergo a ductile fracture during bulk fracture impact testing.

[0069] As indicated from Tables 8 and 11, the normalized bulk fracture toughness range is from 4.1 to 53.7 J/mm. From the existing data the entire range of properties expected for the alloys herein according to the methodology in FIG. **2**, through the identified thickness range of 0.5 to 3.0 mm, can be identified. Increasing thickness results in increasing level of toughness and over the thickness range indicated (i.e. 0.5 to 3.0 mm), the data is estimated to be linear. The lower limit of bulk fracture toughness is identified by taking the lower limit of normalized bulk fracture toughness and multiplying it by the minimum thickness of 0.5 mm. The upper limit of bulk fracture toughness is identified by taking the upper limit of normalized bulk fracture toughness and dividing it by the maximum thickness of 3.0 mm. Thus, the range of bulk fracture toughness calculated for the alloys herein is from 2.0 to 161 J.

Case Example #4 Charpy Un-Notched Specimens Testing

[0070] Slabs with thickness of 50 mm were laboratory cast from the Alloy 7 and Alloy 9 according to the atomic ratios provided in Table 1 and laboratory processed by hot rolling to thickness of 5 and 7 mm and by subsequent cold rolling to thicknesses of 1.2 and 2.5 mm. At each listed thickness, Charpy un-notched specimens were cut from the material. Specimens that were cut from the cold rolled sheet (i.e. the 1.2 mm and 2.5 mm samples) were subsequently annealed at 950° C. for 6 hr as described in the Main Body section of the current application.

[0071] Charpy testing was done by using the Instron SI-1B Pendulum Impact Tester in accordance with the methodology described in the Main Body section of the current application. None of the tested specimens broke during the testing but bent and slip through the anvil. The recorded toughness, which corresponds to the work required to bend specimen and push it through the anvil is listed in Table 12 for both alloys. Examples of unbroken specimens after testing are shown in FIG. **15**.

TABLE 12

Charpy Un-Notch Data For Selected Alloys

Alloy	Thickness (mm)	Unnotched Charpy (J)			Condition
Alloy 7	1.2	20.3	10.8	17.6	Annealed
Alloy 7	2.5	134.2	131.5	147.8	Annealed
Alloy 7	5.0	292.9	287.4	282.0	Hot rolled
Alloy 7	7.0	397.3	—	—	Hot rolled
Alloy 9	1.3	20.3	23.0	23.0	Annealed
Alloy 9	2.5	127.4	139.6	143.7	Annealed
Alloy 9	5.0	313.2	305.1	320.0	Hot rolled
Alloy 9	7.0	405.4	—	—	Hot rolled

This Case Example demonstrates high toughness of alloys herein that do not break in a case of impact testing of un-notched specimens.

Case Example #5 Charpy V-Notch Toughness as a Function of Thickness

[0072] Laboratory slabs from Alloy 7 and Alloy 9 were cast according to the atomic compositions provided in Table 1. Materials were produced at a range of thicknesses for Charpy V-notch impact testing by hot rolling, cold rolling, and annealing as previously described. The approximate thicknesses produced for testing are 1.2 mm, 2.5 mm, 5 mm, and 7 mm. For samples at thickness >2.5 mm, material was cast and hot rolled only, whereas for samples with 1.2 mm and 2.5 mm thicknesses the material was cast, hot rolled, cold rolled, and then annealed at 950° C. for 6 hr as described in the Main Body section of the current application. Charpy V-Notch specimens were cut by wire EDM from the sheet material with each thickness.

[0073] Charpy testing was done by using the Instron SI-1B Pendulum Impact Tester in accordance with the methodology described in the Main Body section of the current application. Three specimens were tested at each thickness for each alloy. The measured Charpy V-notch impact energy for Alloy 7 and Alloy 9 are provided in Table 13 and Table 14, respectively. The Charpy V-notch toughness for alloys herein was measured in a range from 16.3 to 104.4 J. Thickness normalized values of the Charpy V-notched toughness vary from 12.5 to 15.6 J/mm. Note that the Table 13 and Table 14 properties correspond to sheet produced to Step **2** in both FIG. **1** and FIG. **2**, depending on thickness as noted earlier. The trend in measured Charpy V-notch toughness as a function of material thickness for the alloys is shown in FIG. **16** and FIG. **17** for Alloy 7 and Alloy 9, respectively.

TABLE 13

Measured Charpy V-notch Toughness For Alloy 7 As A Function Of Thickness

Sample #	Thickness (mm)	Charpy V-Notch Toughness (J)	Thickness Normalized Charpy V-Notch Toughness (J/mm)
1	1.2	17.6	14.7
2	1.2	16.3	13.6
3	1.2	16.3	13.6
4	2.5	36.6	14.6
5	2.5	35.3	14.1
6	2.5	35.3	14.1
7	5.0	75.9	15.2
8	5.0	75.9	15.2
9	7.0	99.0	14.2
10	7.0	104.4	14.9
11	7.0	97.6	13.9

TABLE 14

Measured Charpy V-notch Toughness For Alloy 9 As A Function Of Thickness

Sample	Thickness (mm)	Charpy V-Notch Toughness (J)	Thickness Normalized Charpy V-Notch Toughness (J/mm)
1	1.2	16.3	13.6
2	1.2	16.3	13.6
3	1.2	17.6	14.7
4	2.5	36.6	14.6
5	2.5	35.3	14.1
6	2.5	33.9	13.6
7	5.0	62.4	12.5
8	5.0	63.7	12.7
9	5.0	62.4	12.5
10	7.0	89.5	12.8
11	7.0	90.8	13.0
12	7.0	89.5	12.8

[0074] This Case Example demonstrates the trend in Charpy V-notch toughness of the alloys herein as a function of sheet thickness. Note that for alloys herein, the measured Charpy V-notch toughness increases with increasing thickness.

[0075] As indicated from Tables 7, 10, 13, and 14, the normalized Charpy V-notched toughness range is from 0.5 to 21.8 J/mm. From the existing data the entire range of properties expected for the alloys here-in according to the methodology in FIG. **2**, through the identified thickness range of 0.5 to 3.0 mm, can be identified. Increasing thickness results in increasing level of toughness and over the thickness range indicated (i.e. 0.5 to 3.0 mm), the data is estimated to be linear. The lower limit of Charpy V-notched toughness is identified by taking the lower limit of normalized Charpy V-notched toughness and multiplying it by the minimum thickness of 0.5 mm. The upper limit of Charpy V-notched toughness is identified by taking the upper limit of normalized Charpy V-notched toughness and dividing it by the maximum thickness of 3.0 mm. Thus, the range of Charpy V-notched toughness calculated for the alloys herein is from 0.2 to 65.4 J.

Case Example #6 Toughness Testing of Hot Band

[0076] Slabs with thickness of 50 mm were laboratory cast from selected alloys listed in Table 16 according to the atomic ratios provided in Table 1 and laboratory processed by hot rolling. Prior to hot rolling, laboratory slabs were preheated in a Lucifer EHS3GT-B18 furnace. The furnace set point varies between 1100° C. to 1250° C., depending on alloy melting point and point in the hot rolling process, with the initial temperatures set higher to facilitate higher reductions, and later temperatures set lower to minimize surface oxidation on the hot band. The slabs were allowed to soak for 40 minutes prior to hot rolling to ensure they reach the target temperature and then pushed out of the tunnel furnace into a Fenn Model 061 2 high rolling mill. The 50 mm casts were hot rolled for 5 to 10 passes though the mill before being allowed to air cool. Final thickness of the hot band materials was from 1.8 to 2.2 mm. Specimens for Charpy V-notch testing and bulk fracture testing were cut by wire EDM from the hot band for each alloy. Charpy V-notch testing and bulk fracture testing were done using the same procedures described in the Main Body section of the current application. For each alloy, two to three specimens were tested by each method.

[0077] Charpy V-notch and bulk fracture testing results are shown in Table 15 and Table 16, respectively. Absorbed energy representing Charpy V-notch toughness of the alloys herein is in a range from 11.9 to 23.7 J for samples with thickness from 1.8 to 2.2 mm. Thickness normalized values of the Charpy V-notched toughness vary from 6.6 to 11.9 J/mm. Note that the Table 15 properties correspond sheet produced in Step **2** in FIG. **2**. Bulk fracture toughness values from alloys herein were measured in a range from 16.3 to 101.7 J for samples with thickness from 1.8 to 2.2 mm. Thickness normalized values of the bulk fracture toughness vary from 8.2 to 46.5 J/mm. Note that the Table 16 properties correspond to sheet produced in Step **2** in FIG. **2**.

[0078] As indicated from Tables 13, 14, and 15, the normalized Charpy V-notched toughness range is from 6.6 to 15.2 J/mm. From the existing data the entire range of properties expected for the alloys here-in according to the methodology in FIG. **1**, through the identified thickness range of 1.5 to 8.0 mm, can be identified. Increasing thickness results in increasing level of toughness and over the thickness range indicated (i.e. 1.5 to 8.0 mm), the data is estimated to be linear. The lower limit of Charpy V-notched toughness is identified by taking the lower limit of normalized Charpy V-notched toughness and multiplying it by the minimum thickness of 1.5 mm. The upper limit of Charpy V-notched toughness is identified by taking the upper limit of normalized Charpy V-notched toughness and dividing it by the maximum thickness of 8.0 mm. Thus, the range of Charpy V-notched toughness calculated for the alloys herein is from 9.9 to 121.6 J.

TABLE 15

Charpy V-Notch Testing Data On ~2 mm Thick Hot Band

Alloy	Charpy V-Notch Toughness (J)			Thickness (mm)	Thickness Normalized Charpy V-Notch Toughness (J/mm)		
Alloy 23	20.7	21.7	21.0	2.1	9.9	10.3	10.0
Alloy 24	23.0	22.4	23.0	2.1	11.0	10.7	11.0
Alloy 25	21.0	21.4	22.4	2.0	10.5	10.7	11.2
Alloy 26	22.4	22.4	22.4	2.1	10.7	10.7	10.7
Alloy 27	21.0	22.7	21.0	2.1	10.0	10.8	10.0
Alloy 28	22.4	23.7	22.0	2.0	11.2	11.9	11.0
Alloy 29	20.3	19.7	20.3	2.0	10.2	9.9	10.2
Alloy 30	21.7	20.7	22.7	2.0	10.9	10.4	11.4
Alloy 31	21.4	21.4	21.7	2.0	10.7	10.7	10.9
Alloy 32	18.6	19.0	19.0	2.1	8.9	9.0	9.0
Alloy 33	14.6	13.6	14.9	1.9	7.7	7.2	7.8
Alloy 34	14.6	12.2	13.6	1.8	8.1	6.8	7.6
Alloy 35	15.6	14.2	14.9	1.9	8.2	7.5	7.8
Alloy 36	13.2	11.9	13.2	1.8	7.3	6.6	7.3
Alloy 37	21.0	19.7	20.0	2.0	10.5	9.9	10.0

TABLE 16

Bulk Fracture Testing Data On ~2 mm Thick Hot Band

Alloy	Bulk Fracture Toughness (J)			Thickness (mm)	Thickness Normalized Bulk Fracture Toughness (J/mm)		
Alloy 8	42.7	41.4	40.3	2.2	19.4	18.8	18.3
Alloy 9	97.6	97.6	93.9	2.2	44.4	44.4	42.7
Alloy 10	91.9	98.6	93.6	2.2	41.8	44.8	42.5
Alloy 11	101.7	93.6	97.6	2.2	46.2	42.5	44.4
Alloy 12	80.0	78.6	81.3	2.1	38.1	37.4	38.7
Alloy 13	75.2	84.1	83.4	2.2	34.2	38.2	37.9
Alloy 14	80.3	85.4	82.0	2.1	38.2	40.7	39.0
Alloy 15	69.1	70.5	69.1	1.9	36.4	37.1	36.4
Alloy 16	31.9	19.7	17.6	2.0	16.0	9.9	8.8
Alloy 17	92.5	94.9	94.9	2.1	44.0	45.2	45.2
Alloy 18	83.4	86.1	84.7	2.2	37.9	39.1	38.5
Alloy 19	94.2	96.9	97.6	2.1	44.9	46.1	46.5
Alloy 20	90.2	89.5	90.5	2.2	41.0	40.7	41.1
Alloy 21	70.5	72.2	73.9	1.9	37.1	38.0	38.9
Alloy 22	16.3	23.0	27.1	2.0	8.2	11.5	13.6
Alloy 23	85.4	84.1	86.1	2.1	40.7	40.0	41.0
Alloy 24	85.1	85.4	84.7	2.1	40.5	40.7	40.3
Alloy 25	87.5	85.1	86.4	2.1	41.7	40.5	41.1
Alloy 26	90.2	90.8	87.5	2.1	43.0	43.2	41.7
Alloy 27	85.4	89.1	88.8	2.1	40.7	42.4	42.3
Alloy 28	86.1	84.7	86.4	2.0	43.1	42.4	43.2
Alloy 29	81.3	84.3	85.1	2.0	40.7	42.2	42.6
Alloy 30	86.1	82.0	84.1	2.0	43.1	41.0	42.1
Alloy 31	86.1	88.1	84.1	2.0	43.1	44.1	42.1
Alloy 32	67.5	63.0	54.9	2.1	32.1	30.0	26.1
Alloy 33	51.9	48.4	52.5	1.9	27.3	25.5	27.6
Alloy 34	51.9	51.5	50.2	1.8	28.8	28.6	27.9
Alloy 35	50.8	50.5	51.2	1.9	26.7	26.6	26.9
Alloy 36	45.4	44.7	46.4	1.8	25.2	24.8	25.8
Alloy 37	78.0	76.9	72.9	2.0	39.0	38.5	36.5

[0079] This Case Example demonstrates Charpy V-notch toughness of the alloys herein in a hot rolled condition (hot band) with a thickness more than 1.4 mm and less than or equal to 5 mm.

Case Example #7 Drop Impact Testing of Selected Alloys

[0080] Slabs with thickness of 50 mm were laboratory cast from selected alloys listed in Table 17 according to the atomic ratios provided in Table 1 and laboratory processed by hot rolling, cold rolling and annealing at 850° C. for 10 min as described in the current application. Final thickness of the cold rolled and annealed sheet was from 1.1 to 1.4 mm. Strips with 100 mm width and approximately 300 mm length were cut from the produced sheet from alloys herein.

[0081] The material being drop impact tested was clamped between two steel plates. The plate under the sample has a 50 mm diameter hole centered about the point of impact. The plate above is a square frame to prevent the material from buckling during testing. The impactor utilized for the testing was made from hardened steel having 12.7 mm in diameter with a 3.18 mm radius as shown in FIG. **18**. The drop height was 1.3 m. The drop carriage traveled along two precision guide rods to maintain alignment. The weight of the drop carriage and additional weights were determined using a calibrated scale. Drop weight as variable by adding and removing weights to allow determination of a highest drop impact energy when no sheet penetration occurred, and no cracks generated during the impact. The results of the drop impact testing of the alloys herein with thickness from 1.1 to 1.4 mm are listed in Table 17 showing highest drop impact energy without penetration for each alloy representing drop impact toughness and varies from 108 to 279 J. Thickness normalized values are in a range from 92 to 234 J/mm. Note that the Table 17 properties correspond to sheet produced in Step **2** in FIG. **1**.

TABLE 17

Drop Impact Testing Of Alloys In Cold Rolled And Annealed State

Alloy	Thickness (mm)	Highest Passing Drop Impact Energy (J)	Thickness Normalized Drop Impact Toughness (J/mm)
Alloy 2	1.1	207	188.2
Alloy 3	1.2	236	196.7
Alloy 4	1.2	207	172.5
Alloy 6	1.2	266	221.7
Alloy 9	1.3	207	159.2
Alloy 10	1.2	177	147.5
Alloy 11	1.2	207	172.5
Alloy 13	1.2	221	184.2
Alloy 14	1.2	250	208.3
Alloy 15	1.2	236	196.7
Alloy 17	1.3	192	147.7
Alloy 18	1.2	177	147.5
Alloy 19	1.4	221	157.9
Alloy 20	1.2	250	208.3
Alloy 21	1.2	279	232.5
Alloy 23	1.2	207	172.5
Alloy 24	1.2	208	173.3
Alloy 25	1.2	208	173.3
Alloy 26	1.2	221	184.2
Alloy 27	1.2	236	196.7
Alloy 28	1.2	221	184.2
Alloy 29	1.2	250	208.3
Alloy 30	1.2	221	184.2
Alloy 31	1.2	236	196.7
Alloy 32	1.2	192	160.0
Alloy 33	1.2	192	160.0
Alloy 34	1.2	108	90.0
Alloy 35	1.2	221	184.2
Alloy 36	1.2	177	147.5
Alloy 37	1.2	250	208.3

[0082] This Case Example demonstrates drop impact toughness of the alloys herein in a cold rolled and annealed state with a sheet thickness equal or more than 0.5 mm and less or equal to 1.4 mm.

[0083] As indicated from Table 17, the normalized drop impact toughness range is from 90.0 to 232.5 J/mm. From the existing data the entire range of properties expected for the alloys here-in according to the methodology in FIG. **2**, through the identified thickness range of 0.5 to 3.0 mm, can be identified. Increasing thickness results in increasing level of toughness and over the thickness range indicated (i.e. 0.5 to 3.0 mm), the data is estimated to be linear. The lower limit of drop impact toughness is identified by taking the lower limit of normalized drop impact toughness and multiplying it by the minimum thickness of 0.5 mm. The upper limit of drop impact toughness is identified by taking the upper limit of normalized drop impact toughness and dividing it by the maximum thickness of 3.0 mm. Thus, the range of drop impact toughness calculated for the alloys herein is from 45.0 to 696.9 J.

Case Example 8 Bulk Fracture of Alloy 24 at 4 mm Thickness

[0084] A slab of Alloy 24 was cast according to the atomic ratios provided in Table 1 and laboratory processed by hot rolling. Prior to hot rolling, the slab was preheated in a Lucifer EHS3GT-B18 furnace. The slab was allowed to soak for 40 minutes prior to hot rolling to ensure that the slab reached the target temperature. The slab was pushed out of the furnace into a Fenn Model 061 2-high rolling mill. The 50 mm slab was then hot rolled to a final thickness of approximately 4 mm. Specimens for bulk fracture testing were cut by wire-EDM from the hot band. Bulk fracture testing was performed according to the procedures described in the Main Body section of this application.

[0085] The measured bulk fracture energy is provided in Table 19. All tested samples broke and subsequently stopped the hammer. Absorbed energy for the bulk fracture specimens were all measured at 119 J. Note that these measured values are slightly less than the maximum 120 J energy for the test. An image of a tested 4 mm thick bulk fracture sample is provided in FIG. **19**.

TABLE 19

Bulk Fracture Toughness Of Alloy 24 At 4 mm Thickness

Sample	Bulk Fracture Toughness (J)	Thickness Normalized Bulk Fracture Toughness (J/mm)
1	119	29.8
2	119	29.9
3	119	29.9

[0086] This Case Example demonstrates that for the alloys herein, bulk fracture toughness at ≥4 mm thickness is at the limit measurable by current test equipment. The measured bulk fracture toughness is almost equal to the maximum energy that can be imparted by the hammer, thereby resulting in inaccurate measurements.

[0087] As indicated from Tables 16 and 19, the normalized bulk fracture toughness range is from 8.2 to 46.5 J/mm. Note that due to experimental capacity limitations, the maximum thickness which could be tested in this laboratory system is ~4 mm. From the existing data the entire range of properties expected for the alloys herein according to the methodology in FIG. **1**, through the identified thickness range of 1.5 to 8.0 mm, can be identified. Increasing thickness results in increasing level of toughness and over the thickness range indicated (i.e. 1.5 to 8.0 mm), the data is estimated to be linear. The lower limit of bulk fracture toughness is identified by taking the lower limit of normalized bulk fracture toughness and multiplying it by the minimum thickness of 1.5 mm. The upper limit of bulk fracture toughness is identified by taking the upper limit of normalized bulk fracture toughness and dividing it by the maximum thickness of 8.0 mm. Thus, the range of bulk fracture toughness calculated for the alloys herein is from 12.3 to 372 J.

Case Example 9 Drop Impact Testing of Alloy 24 at 4 mm Thickness

[0088] A slab of Alloy 24 was cast according to the atomic ratios provided in Table 1 and laboratory processed by hot rolling. Prior to hot rolling, the slab was preheated in a Lucifer EHS3GT-B18 furnace. The slab was allowed to soak for 40 minutes prior to hot rolling to ensure that the slab reached the target temperature. The slab was pushed out of the furnace into a Fenn Model 061 2-high rolling mill. The 50 mm slab was then hot rolled to a final thickness of approximately 4 mm. Drop impact testing was performed according to the procedures described in the Main Body section of this application. Total impact energy of 432 J was used which is the maximum available with this test fixture.

[0089] An image of a tested 4 mm thick drop impact sample is provided in FIG. **20** and FIG. **21**. Note that the material did not rupture when impacted with 432 J. A small amount of deformation was observed in the material, as shown by the impact dimple in the sheet. This Case Example demonstrates that drop impact testing alloys herein at ≥4 mm thickness does not result in failure of the material with the maximum available impact energy.

Case Example #10 Drop Impact Testing of Selected Alloys in Hot Rolled State

[0090] Slabs were cast from alloys listed in Table 20 according to the atomic ratios provided in Table 1 and laboratory processed by hot rolling. Prior to hot rolling, the slab was preheated in a Lucifer EHS3GT-B18 furnace. The slab was allowed to soak for 40 minutes prior to hot rolling to ensure that the slab reached the target temperature. The slab was pushed out of the furnace into a Fenn Model 061 2-high rolling mill. The 50 mm slab was then hot rolled to a final thickness from 2.0 to 3.2 mm. Strips with 100 mm width and approximately 300 mm length were cut from the produced sheet from alloys herein.

[0091] The material being drop impact tested was clamped between two steel plates. The plate under the sample has a 50 mm diameter hole centered about the point of impact. The plate above is a square frame to prevent the material from buckling during testing. The impactor utilized for the testing was made from hardened steel having 12.7 mm in diameter with a 3.18 mm radius as shown in FIG. **18**. The drop height was 1.3 m. The drop carriage traveled along two precision guide rods to maintain alignment. The weight of the drop carriage and additional weights were determined using a calibrated scale. Drop weight was variable by adding and removing weights to allow determination of a highest drop impact energy when no sheet penetration occurred, and no cracks generated during the impact. The results of the drop impact testing of the alloys herein with thickness from 2.0 to 3.2 mm are listed in Table 20 showing highest drop impact energy without penetration for each alloy representing drop impact toughness and varies from 157 to 481 J. Thickness normalized values are in a range from 80 to 154 J/mm. Note that the Table 20 properties correspond to sheet produced in Step **2** in FIG. **1**.

TABLE 20

Drop Impact Testing Of Alloys In Hot Rolled State

Alloy	Thickness (mm)	Highest Passing Drop Impact Energy (J)	Thickness Normalized Drop Impact Toughness (J/mm)
Alloy 02	2.0	217	111
Alloy 03	2.0	232	119
Alloy 09	2.2	262	122
Alloy 09	3.1	481	154
Alloy 11	2.2	252	111
Alloy 11	3.2	481	149
Alloy 13	2.3	217	96
Alloy 16	2.1	232	112
Alloy 16	3.1	439	142
Alloy 19	2.1	187	89
Alloy 19	3.1	394	126
Alloy 29	2.0	232	119
Alloy 36	2.0	157	80
Alloy 39	2.9	246	84

[0092] This Case Example demonstrates drop impact toughness of the alloys herein in a hot rolled state with a sheet thickness equal or more than 2.0 mm and less or equal to 3.2 mm.

[0093] As indicated from Case Examples 9 and 10, the normalized drop impact toughness range is from 80 to 154 J/mm. The maximum thickness which could be tested was ~4 mm. From the existing data the entire range of properties expected for the alloys herein according to the methodology in FIG. **1**, through the identified thickness range of 1.5 to 8.0 mm, can be identified. Increasing thickness results in increasing level of toughness and over the thickness range indicated (i.e. 1.5 to 8.0 mm), the data is estimated to be linear. The lower limit of drop impact toughness is identified by taking the lower limit of normalized drop impact toughness and multiplying it by the minimum thickness of 1.5 mm. The upper limit of drop impact toughness is identified by taking the upper limit of normalized drop impact toughness and dividing it by the maximum thickness of 8.0 mm. Thus, the range of drop impact toughness calculated for the alloys herein is from 120 J to 1232 J.

1. A method to achieve a strength/ductility characteristic in a metal comprising:

a. supplying a metal alloy comprising at least 70 atomic percent Fe, at least 9.0 atomic percent Mn, at least 0.4 atomic percent Al, and at least two elements selected from Cr, Si or C, melting and cooling at a rate of ≤250 K/s to a thickness of 25.0 mm to 500.0 mm;

b. processing said alloy into sheet by heating and reducing said thickness to form to a thickness of 1.5 mm to 8.0 mm wherein the sheet exhibits an ultimate tensile strength (TS) of 650 MPa to 1500 MPa, a yield strength (YS) at 0.2% offset of 200 MPa to 1,000 MPa and an elongation (E) from 10% to 70%, wherein the alloy further indicates a strength ductility product (TS×E) in the range of 15,000 MPa % to 75,000 MPa %.

2. The method of claim **1** wherein the alloy in (a) contains 70 to 80 at. % Fe, 9.0 to 17.0 at. % Mn, and 0.4 to 6.7 at. % Al.

3. The method of claim **1** wherein Cr is selected and is present at a level of 0.2 at. % to 6.3 at. %.

4. The method of claim **1** wherein Si is selected and is present at a level of 0.3 at. % to 6.3 at. %.

5. The method of claim **1** wherein C is selected and is present at a level of 0.3 at. % to 2.7 at. %.

6. The method of claim **1** wherein said alloy is substantially free of nickel and copper such that nickel and copper are present at a level of 0 to 5000 ppm.

7. The method of claim **1** wherein the alloy in (a) indicates a solidus temperature from 1300° C. to 1450° C., a liquidus temperature from 1400° C. to 1550° C., and a liquidus to solidus gap from 30° C. to 150° C.

8. The method of claim **1** wherein the alloy sheet in (b) has a density from 7.3 g/cm3 to 7.9 g/cm3.

9. The method of claim **1** wherein said alloy sheet in (b) indicates an area under a stress-strain curve up to fracture in the range of from 150 to 600 N/mm2.

10. The method of claim **1** wherein the alloy sheet in (b) exhibits a Charpy V-notched toughness of 10 J to 150 J.

11. The method of claim **1** wherein the alloy sheet in (b) exhibits a thickness normalized Charpy V-Notched toughness from 5 to 25 J/mm.

12. The method of claim **1** wherein the alloy sheet in (b) exhibits a bulk fracture toughness from 10 to 400 J.

13. The method of claim **1** wherein the alloy sheet in (b) exhibits a thickness normalized bulk fracture toughness from 5 to 50 J/mm.

14. The method of claim **1** wherein the alloy sheet in (b) exhibits a drop impact toughness of 100 J to 1250 J.

15. The method of claim **1** wherein the alloy sheet in (b) exhibits a thickness normalized drop impact toughness from 75 J/mm to 160 J/mm.

16. The method of claim **1** wherein said alloy sheet in (b) is positioned in a storage tank, freight car, or railway tank car.

17. The method of claim **1** wherein said alloy sheet formed in (b) is positioned in a vehicular frame, vehicular chassis, or vehicular panel.

18. A method to achieve a strength/ductility characteristic in a metal comprising:

a. supplying a metal alloy comprising at least 70 atomic percent Fe, at least 9.0 atomic percent Mn, at least 0.4 atomic percent Al, and at least two elements selected from Cr, Si or C, melting and cooling at a rate of ≤250 K/s to a thickness of 25.0 mm to 500.0 mm;

b. processing said alloy into sheet by heating and reducing said thickness to form to a thickness of 1.5 mm to 8.0 mm;

c. processing said alloy into sheet by reducing said thickness without heating to form to a thickness of 0.5 mm to 3.0 mm wherein the sheet exhibits an ultimate tensile strength (TS) of 650 MPa to 1500 MPa, a yield strength (YS) at 0.2% offset of 200 MPa to 1000 MPa and an elongation (E) from 10.0% to 90.0%, wherein the alloy further indicates a strength ductility product (TS×E) in the range of 10,000 MPa % to 80,000 MPa %.

19. The method of claim **18** wherein the alloy in (a) contains 70 to 80 at. % Fe, 9.0 to 17.0 at. % Mn, and 0.4 to 6.7 at. % Al.

20. The method of claim **18** wherein Cr is selected and is present at a level of 0.2 at. % to 6.3 at. %.

21. The method of claim **18** wherein Si is selected and is present at a level of 0.3 at. % to 6.3 at. %.

22. The method of claim **18** wherein C is selected and is present at a level of 0.3 at. % to 2.7 at. %.

23. The method of claim **18** wherein said alloy is substantially free of nickel and copper such that nickel and copper are present at a level of 0 to 5000 ppm.

24. The method of claim **18** wherein the alloy in (a) indicates a solidus temperature from 1300° C. to 1450° C., a liquidus temperature from 1400° C. to 1550° C., and a liquidus to solidus gap from 30° C. to 150° C.

25. The method of claim **18** wherein the alloy sheet in (b) has a density from 7.3 g/cm3 to 7.9 g/cm3.

26. The method of claim **18** wherein the alloy sheet in (c) may be annealed from 600° C. up to the solidus temperature.

27. The method of claim **18** wherein said alloy sheet in (c) indicates an area under a stress-strain curve up to fracture in the range of from 100 to 700 N/mm2.

28. The method of claim **18** wherein the alloy sheet in (c) exhibits a Charpy V-Notched toughness of 0.5 to 75 J.

29. The method of claim **18** wherein the alloy sheet in (c) exhibits a thickness normalized Charpy V-Notched toughness from 0.5 J/mm to 25 J/mm.

30. The method of claim **18** wherein the impacted alloy sheet in (c) exhibits a bulk fracture toughness from 2 J to 175 J.

31. The method of claim **18** wherein the alloy sheet in (c) exhibits a thickness normalized bulk fracture toughness from 1 to 60 J/mm.

32. The method of claim **18** wherein the impacted alloy sheet in (c) exhibits a drop impact toughness of 40 J to 700 J.

33. The method of claim **18** wherein the alloy sheet in (c) exhibits a thickness normalized drop impact toughness from 75 J/mm to 250 J/mm.

34. The method of claim **18** wherein said alloy sheet in (c) is positioned in a storage tank, freight car, or railway tank car.

35. The method of claim **18** wherein said alloy sheet formed in (c) is positioned in a vehicular frame, vehicular chassis, or vehicular panel.

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