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(54) Title: LOW CARBON ALLOY STEEL TUBE HAVING ULTRA HIGH STRENGTH AND EXCELLENT TOUGHNES AT
LOW TEMPERATURE AND METHOD OF MANUFACTURING THE SAME

(57) Abstract: A low carbon alloy steel tube and a method of manufacturing the same, in which the steel tube consists essentially
of, by weight: about 0.06% to about 0.18% carbon; about 0.5% to about 1.5% manganese; about 0.1% to about 0.5% silicon; up
to about 0.015% sulfur; up to about 0.025% phosphorous; up to about 0.50% nickel; about 0.1% to about 1.0% chromium; about
0.1% to about 1.0% molybdenum; about 0.01% to about 0.10% vanadium; about 0.01% to about 0.10% titanium; about 0.05% to
about 0.35% copper; about 0.010% to about 0.050% aluminum; up to about 0.05% niobium; up to about 0.15% residual elements;
and the balance iron and incidental impurities. The steel has a tensile strength of at least about 145 ksi and exhibits ductile behavior
at temperatures as low as -60 °C.



WO 2005/035800 A1

**LOW CARBON ALLOY STEEL TUBE HAVING ULTRA HIGH STRENGTH
AND EXCELLENT TOUGHNESS AT LOW TEMPERATURE AND METHOD OF
MANUFACTURING THE SAME**

Related Application

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 60/509,806, filed on October 10, 2003, and U.S. Non-Provisional Patent Application No. , filed on October 5, 2004.

Background of the Invention

[0002] The present invention relates to a low carbon alloy steel tube having ultra high strength and excellent toughness at a low temperature and also to a method of manufacturing such a steel tube. The steel tube is particularly suitable for making components for containers for automotive restraint system components, an example of which is an automotive airbag inflator.

[0003] Airbag inflators for vehicle occupant restraint systems are required to meet strict structural and functional standards. Therefore, strict procedures and tolerances are imposed on the manufacturing process. While field experience indicates that the industry has been successful in meeting past structural and functional standards, improved and/or new properties are necessary to satisfy the evolving requirements, while at the same time a continuous reduction in the manufacturing costs is also important.

[0004] Airbags or supplemental restraint systems are an important safety feature in many of today's vehicles. In the past, air bag systems were of the type employing explosive chemicals, but they are expensive, and due to environmental and recycling problems, in recent years, a new type of inflator has been developed using an accumulator made of a steel tube filled with argon gas or the like, and this type is increasingly being used.

[0005] The above-mentioned accumulator is a container which at normal times maintains the gas or the like at a high pressure which is blown into an airbag at the time of the collision of an automobile, in a single or multiple stage burst. Accordingly, a steel tube used as such an accumulator is to receive a stress at a high strain rate in an extremely short period of time. Therefore, compared with a simple structure such as an ordinary pressure cylinder, the above-described steel tube is required to have superior dimensional accuracy, workability, and weldability, and it must also have high strength, toughness, and excellent resistance to bursting. The dimensional accuracy is important to ensure a very precise volume of gas that blows the airbag.

[0006] Cold forming properties are very important in tubular members used to manufacture accumulators since they are formed to final shape after the seamless tube is manufactured. Different shapes depending on the vessel configuration shall be obtained by cold forming. It is crucial to obtain pressure vessels without cracks and superficial defects after cold forming. Moreover, it is also vital to have very good toughness even at low temperatures after cold forming.

[0007] The steel that has been developed has very good weldability, not requiring for this application either preheating prior to welding, or post weld heat treatment. The carbon equivalent, as defined by the formula,

$$Ceq = \%C + \%Mn/6 + (\%Cr+\%Mo+\%V)/5 + (\%Ni+\%Cu)/15$$

should be less than about 0.63% in order to obtain the required weldability. In the preferred embodiment of this invention, the carbon equivalent as defined above should be less than about 0.60%, in order to better guarantee weldability.

[0008] To produce a gas container, a cold-drawn tube made according the present invention is cut to length and then cold formed using different known technologies (such as crimping, swaging, or the like) in order to obtain the desired shape. Alternatively, a welded tube could be used. Subsequently, to produce the accumulator, an end cap and a diffuser are welded to each end of the container by any suitable technology such as friction welding, gas tungsten arc welding or laser welding. These welds are highly critical and as such require considerable labor, and in certain instances testing to assure weld integrity throughout the pressure vessel and airbag deployment. It has been observed that these welds can crack or fail, thus, risking the integrity of the accumulator, and possibly the operation of the airbag.

[0009] The inflators are tested to assure that they retain their structural integrity during airbag deployment. One of such tests is the so call burst test. This is a destructive-type test in which a canister is subjected to internal pressures significantly higher than those expected during normal operational use, i.e., airbag deployment. In this test, the inflator is subjected to increasing internal pressures until rupture occurs.

[0010] In reviewing the burst test results and studying the test canister specimens from these tests, it has been found that fracture occurs through different alternative ways: ductile fracture, brittle fracture, and sometimes a combination of these two modes. It has been observed that in ductile fracture an outturned rupture exemplified by an opened bulge (such as would be exhibited by a bursting bubble) occurs. The ruptured surface is inclined approximately 45 degrees with respect to the tube outer surface, and is localized within a subject area. In a brittle fracture, on the other hand, a non-arresting longitudinal crack along

the length of the inflator is exhibited, which is indicative of a brittle zone in the material. In this case, the fracture surface is normal to the tube outer surface. These two modes of fracture have distinctive surfaces when observed under a scanning electron microscope – dimples are characteristic of ductile fracture, while cleavage is an indication of brittleness. [0011] At times, a combination of these two fracture modes can be observed, and brittle cracks can propagate from the ductile, ruptured area. Because the whole system, including the airbag inflator, may be utilized in vehicles operating in very different climates, it is crucial that the material exhibits ductile behavior over a wide temperature range, from very cold up to warm temperatures.

Summary of the Invention

[0012] The present invention relates to a low carbon alloy steel tube suitable for cold forming having ultra high strength (UTS 145 ksi minimum), and, consequently, a very high burst pressure. Moreover, the steel has excellent toughness at low temperature, with guaranteed ductile behavior at -60 °C, i.e., a ductile-to-brittle transition temperature (DBTT) below -60° C, and possibly even as low as -100 °C. The present invention also relates to a process of manufacturing such a steel tube.

[0013] The material of the present invention is designed to make components for containers for automotive restraint system components, an example of which is an automotive airbag inflator.

Description of the Preferred Embodiments

[0014] While the present invention is susceptible of embodiment in various forms, it will hereinafter be described a presently preferred embodiment with the understanding that the present disclosure is to be considered an exemplification of the invention and is not intended to limit the invention to the specific embodiment illustrated.

[0015] The present invention relates to a steel tubing to be used for stored gas inflator pressure vessels. More particularly, the present invention relates to a low carbon ultra high strength steel grade for seamless pressure vessel applications with guaranteed ductile behavior at -60 °C, i.e., a ductile-to-brittle transition temperature below -60 °C.

[0016] More particularly, the present invention relates to a chemical composition and a manufacturing process to obtain a seamless steel tubing to be used to manufacture an inflator.

[0017] A schematic illustration of a method of producing the seamless low carbon ultra high strength steel could be as follows:

1. Steel making
2. Steel casting

3. Tue hot rolling
4. Hot-rolled hollow finishing operations
5. Cold drawing
6. Heat treating
7. Cold-drawn tube finishing operations

[0018] One of the main objectives of the steel-making process is to refine the iron by removal of carbon, silicon, sulfur, phosphorous, and manganese. In particular, sulfur and phosphorous are prejudicial for the steel because they worsen the mechanical properties of the material. Ladle metallurgy is used before or after basic processing to perform specific purification steps that allow faster processing in the basic steel making operation.

[0019] The steel-making process is performed under an extreme clean practice in order to obtain a very low sulfur and phosphorous content, which in turn is crucial for obtaining the high toughness required by the product. Accordingly, the objective of an inclusion level of 2 or less –thin series-, and level 1 or less –heavy series- under the guidelines of ASTM E45 Standard - Worst Field Method (Method A) has been imposed. In the preferred embodiment of this invention, the maximum microinclusion content as measured according to the above mentioned Standard should be:

Inclusion Type	Thin	Heavy
A	0.5	0
B	1.5	1.0
C	0	0
D	1.5	0.5

[0020] Furthermore, the extreme clean practice allows obtaining oversize inclusion content with 30 μm or less in size. These inclusion contents are obtained limiting the total oxygen content to 20 ppm.

[0021] Extreme clean practice in secondary metallurgy is performed by bubbling inert gases in the ladle furnace to force the inclusion and impurities to float. The production of a fluid slag capable of absorbing impurities and inclusions, and the inclusions' size and shape modification by the addition of SiCa to the liquid steel, produce high quality steel with low inclusion content.

[0022] The chemical composition of the obtained steel shall be as follows, in each case “%” means “mass percent”:

Carbon (C)

[0023] C is an element that inexpensively raises the strength of the steel, but if its content is less than 0.06% it is difficult to obtain the desired strength. On the other hand, if the steel has a C content greater than 0.18%, then cold workability, weldability, and toughness decrease. Therefore, the C content range is 0.06% to 0.18%. A preferred range for the C content is 0.07% to 0.12%, and an even more preferred range is 0.08 to 0.11%.

Manganese (Mn)

[0024] Mn is an element which is effective in increasing the hardenability of the steel, and therefore it increases strength and toughness. If its content is less than 0.5% it is difficult to obtain the desired strength, whereas if it exceeds 1.5%, then banding structures become marked, and toughness decreases. Accordingly, the Mn content is 0.5% to 1.5%. However, a preferred Mn range is 1.00% to 1.40%, and a more preferred range is 1.03% to 1.18%.

Silicon (Si)

[0025] Si is an element which has a deoxidizing effect during steel making process and also raises the strength of the steel. If Si content is less than 0.10%, the steel is susceptible to oxidation, on the other hand if it exceeds 0.50%, then both toughness and workability decrease. Therefore, the Si content is 0.1% to 0.5%. A preferred Si range is 0.15% to 0.35%.

Sulfur (S)

[0026] S is an element that causes the toughness of the steel to decrease. Accordingly, the S content is limited to 0.015% maximum. A preferred maximum value is 0.010%, and a more preferred maximum value is 0.003%.

Phosphorous (P)

[0027] P is an element that causes the toughness of the steel to decrease. Accordingly, the P content is limited to 0.025% maximum. A preferred maximum value is 0.015%, and a more preferred maximum value is 0.012%.

Nickel (Ni)

[0028] Ni is an element that increases the strength and toughness of the steel, but it is very costly, therefore the Ni is limited to 0.50% maximum. A preferred maximum value is 0.20% and a more preferred maximum value is 0.10%.

Chromium (Cr)

[0029] Cr is an element which is effective in increasing the strength, toughness, and corrosion resistance of the steel. If its content is less than 0.10% it is difficult to obtain the

desired strength, whereas if it exceeds 1.0%, then toughness at the welding zones decreases markedly. Accordingly, the Cr content is 0.1% to 1.0%. However, a preferred Cr range is 0.55 to 0.80%, and a more preferred range is 0.63% to 0.73%.

Molybdenum (Mo)

[0030] Mo is an element which is effective in increasing the strength of the steel and contributes to retard the softening during tempering. If its content is less than 0.10% it is difficult to obtain the desired strength, whereas if it exceeds 1.0%, then toughness at the welding zones decreases markedly. Accordingly, Mo content is 0.1% to 1.0%. However, this ferroalloy is expensive, forcing the necessity to lower the maximum content. Therefore, a preferred Mo range is 0.30% to 0.50%, and a more preferred range is 0.40% to 0.45%.

Vanadium (V)

[0031] V is an element which is effective in increasing the strength of the steel, even if added in small amounts, and allows to retard the softening during tempering. V content is found to be optimum from 0.01% to 0.10%. However, this ferroalloy is expensive, forcing the necessity to lower the maximum content. Therefore, a preferred V range is 0.01% to 0.07%, and a more preferred range is 0.03% to 0.05%.

Titanium (Ti)

[0032] Ti is an element which is effective in increasing the strength of the steel, even if added in small amounts. Ti content is found to be optimum from 0.01% to 0.10%. However, this ferroalloy is expensive, forcing the necessity to lower the maximum content. Therefore, a preferred Ti range is 0.01% to 0.05%, and a more preferred range is 0.025% to 0.035%.

Copper (Cu)

[0033] This element improves the corrosion resistance of the pipe, therefore the Cu content is in the range of 0.05% to 0.35%, and a preferred range is 0.15% to 0.30%.

Aluminum (Al)

[0034] This element is added to the steel during the steel making process to reduce the inclusion content and to refine the steel grain. A preferred Al content is 0.010% to 0.050%.

[0035] Preferred ranges for other elements not listed above are as follows:

<u>Element</u>	<u>Weight</u>
Niobium	0.05% max
Sn	0.05% max

Sb	0.05% max
Pb	0.05% max
As	0.05% max

[0036] Residual elements in a single ladle of steel used to produce tubing or chambers shall be:

$$\text{Sn+Sb+Pb+As} \leq 0.15\% \text{ max, and}$$

$$\text{S+P} \leq 0.025$$

[0037] The next step is the steel casting to produce a solid steel bar capable of being pierced and rolled to form a seamless steel tube. The steel is cast in the steel shop into a round solid billet, having a uniform diameter along the steel axis.

[0038] The solid cylindrical billet of ultra high clean steel is heated to a temperature of about 1200 °C to 1300 °C, and at this point undergoes the rolling mill process. Preferably, the billet is heated to a temperature of about 1250 °C, and then passed through the rolling mill. The billet is pierced, preferably utilizing the known Manessmann process, and subsequently the outside diameter and wall thickness are substantially reduced while the length is substantially increased during hot rolling. For example, a 148 mm outside diameter solid bar is hot rolled into a 48.3 mm outside diameter hot-rolled tube, with a wall thickness of 3.25 mm.

[0039] The cross-sectional area reduction, measured as the ratio of the cross-sectional area of the solid billet to the cross-sectional area of the hot-rolled tube, is important in order to obtain a refined microstructure, necessary to get the desired mechanical properties.

Therefore, the minimum cross-sectional area reduction is 15:1, with preferred and most preferred minimum cross-sectional area reductions of 20:1 and 25:1, respectively.

[0040] The seamless hot-rolled tube of ultra high clean steel so manufactured is cooled to room temperature. The seamless hot-rolled tube of ultra high clean steel so manufactured has an approximately uniform wall thickness, both circumferentially around the tube and longitudinally along the tube axis.

[0041] The hot-rolled tube is then passed through different finishing steps, for example cut in length into 2 to 4 pieces, and its ends cropped, straightened at known rotary straightening equipment if necessary, and non-destructively tested by one or more of the different known techniques, like electromagnetic testing or ultrasound testing.

[0042] The surface of each piece of hot-rolled tube is then properly conditioned for cold drawing. This conditioning includes pickling by immersion in acid solution, and applying an appropriate layer of lubricants, like the known zinc phosphate and sodium estearathe

combination, or reactive oil. After surface conditioning, the seamless tube is cold drawn, pulling it through an external die that has a diameter smaller than the outside diameter of the tube being drawn. In most cases, the internal surface of the tube is also supported by an internal mandrel anchored to one end of a rod, so that the mandrel remains close to the die during drawing. This drawing operation is performed without the necessity of previously heating the tube above room temperature.

[0043] The seamless tube is so cold drawn at least once, each pass reducing both the outside diameter and the wall thickness of the tube. The cold-drawn steel tube so manufactured has a uniform outside diameter along the tube axis, and a uniform wall thickness both circumferentially around the tube and longitudinally along the tube axis. The so cold-drawn tube has an outside diameter preferably between 10 and 70 mm, and a wall thickness preferably from 1 to 4 mm.

[0044] The cold-drawn tube is then heat treated in an austenizing furnace at a temperature of at least the upper austenizing temperature, or A_{c3} (which, for the specific chemistry disclosed herein, is about 880 °C), but preferably above about 920 °C and below about 1050 °C. This maximum austenizing temperature is imposed in order to avoid grain coarsening. This process can be performed either in a fuel furnace or in an induction-type furnace, but preferably in the latter. The transit time in the furnace is strongly dependent on the type of furnace utilized. It has been found that the high surface quality required by this application is better obtained if an induction type furnace is utilized. This is due to the nature of the induction process, in which very short transit times are involved, precluding oxidation to occur. Preferably, the austenizing heating rate is at least about 100 °C per second, but more preferably at least about 200 °C per second. The extremely high heating rate and, as a consequence, very low heating times, are important for obtaining a very fine grain microstructure, which in turn guarantees the required mechanical properties.

[0045] Furthermore, an appropriate filling factor, defined as the ratio of the round area defined by the outer diameter of the tube to the round area defined by the coil inside diameter of the induction furnace, is important for obtaining the required high heating rates. The minimum filling factor is about 0.16, and a preferred minimum filling factor is about 0.36.

[0046] At or close to the exit zone of the furnace the tube is quenched by means of an appropriate quenching fluid. The quenching fluid is preferably water or water-based quenching solution. The tube temperature drops rapidly to ambient temperature, preferably at a rate of at least about 100 °C per second, more preferably at a rate of at least about 200 °C

per second. This extremely high cooling rate is crucial for obtaining a complete microstructure transformation.

[0047] The steel tube is then tempered with an appropriate temperature and cycle time, at a temperature below Ac1. Preferably, the tempering temperature is between about 400-600 °C, and more preferably between about 450-550 °C. The soaking time shall be long enough to guarantee a very good temperature homogeneity, but if it is too long, the desired mechanical properties are not obtained. Therefore, soaking times of between about 2-30 minutes, preferably between about 4-20 minutes, have been utilized. The tempering process is performed preferably in a protective reducing or neutral atmosphere to avoid decarburizing and oxidation of the tube.

[0048] The ultra high strength steel tube so manufactured is passed through different finishing steps, straightened at known rotary straightening equipment, and non-destructively tested by one or more of the different known techniques. Preferably, for this kind of applications tubes should be tested by means of both known ultrasound and electromagnetic techniques.

[0049] The tubing after heat treatment can be chemically processed to obtain a tube with a desirable appearance and very low surface roughness. For example, the tube could be pickled in a sulfuric acid and hydrochloric acid solution, phosphated using zinc phosphate, and oiled using a petroleum-based oil, a water-based oil, or a mineral oil.

[0050] The steel tube obtained by the described method shall have the following mechanical properties in order to comply with the requirements stated for the invention:

Yield Strength	about 125 ksi (862 MPa) minimum, more preferably 135 ksi (930 Mpa) minimum
Tensile Strength	about 145 ksi (1000 MPa) minimum
Elongation	about 9% minimum
Hardness	about 40 HRC maximum, more preferably 37 HRC maximum.

[0051] The yield strength, tensile strength, elongation, and hardness test shall be performed according to the procedures described in the Standards ASTM E8 and ASTM A370. For the tensile test, a full size specimen for evaluating the whole tubular section is preferred.

[0052] Flattening testing shall conform to the requirements of Specification DOT 39 of 49 CFR, Paragraph 178.65. Therefore, a tube section shall not crack when flattened with a 60 degree angled V-shaped tooling, until the opposite sides are 6 times the tube wall thickness apart. This test is fully met by the steel developed.

[0053] In order to obtain a good balance between strength and toughness, the prior (sometimes referred to as former) austenitic grain size shall be preferably 7 or finer, and more preferably 9 or finer, as measured according to ASTM E-112 Standard. This is accomplished thanks to the extremely short heating cycle during austenitizing.

[0054] The steel tube obtained by the described method shall have the stated properties in order to comply with the requirements stated for the invention.

[0055] The demand of the industry is continuously pushing roughness requirements to lower values. The present invention has a good visual appearance, with, for example, a surface finish of the finished tubing of 3.2 microns maximum, both at the external and internal surfaces. This requirement is obtained through cold drawing, short austenizing times, reducing or neutral atmosphere tempering, and an adequate surface chemical conditioning at different steps of the process.

[0056] A hydroburst pressure test shall be performed by sealing the ends of the tube section, for example, by welding flat steel plates to the ends of the tube. It is important that a 300 mm tube section remains constraint free so that full hoop stress can develop. The pressurization of the tube section shall be performed by pumping oil, water, alcohol or a mixture of them.

[0057] The burst test pressure requirement depends on the tube size. When burst tested, the ultra high strength steel seamless tube has a guaranteed ductile behavior at -60 °C. Tests performed on the samples produced show that this grade has a guaranteed ductile behavior at -60 °C, with a ductile-to-brittle transition temperature below -60 °C.

[0058] The inventors have found that a far more representative validation test is the burst test, performed both at ambient and at low temperature, instead of Charpy impact test (according to ASTM E23). This is due to the fact that relatively thin wall thicknesses and small outside diameter in these products are employed, therefore no standard ASTM specimen for Charpy impact test can be machined from the tube in the transverse direction. Moreover, in order to get this subsize Charpy impact probe, a flattening deformation has to be applied to a curved tube probe. This has a sensible effect on the steel mechanical properties, in particular the impact strength. Therefore, no representative impact test is obtained with this procedure.

We claim:

1. A low carbon alloy steel tube consisting essentially of, by weight: about 0.06% to about 0.18% carbon; about 0.5% to about 1.5% manganese; about 0.1% to about 0.5% silicon; up to about 0.015% sulfur; up to about 0.025% phosphorous; up to about 0.50% nickel; about 0.1% to about 1.0% chromium; about 0.1% to about 1.0% molybdenum; about 0.01% to about 0.10% vanadium; about 0.01% to about 0.10% titanium; about 0.05% to about 0.35% copper; about 0.010% to about 0.050% aluminum; up to about 0.05% niobium; up to about 0.15% residual elements; and the balance iron and incidental impurities, wherein the steel tube has a tensile strength of at least about 145 ksi and has a ductile-to-brittle transition temperature below -60° .
2. The low carbon alloy steel tube of claim 1, wherein the steel tube consists essentially of, by weight: about 0.07% to about 0.12% carbon; about 1.00% to about 1.40% manganese; about 0.15% to about 0.35% silicon; up to about 0.010% sulfur; up to about 0.015% phosphorous; up to about 0.20% nickel; about 0.55% to about 0.80% chromium; about 0.30% to about 0.50% molybdenum; about 0.01% to about 0.07% vanadium; about 0.01% to about 0.05% titanium; about 0.15% to about 0.30% copper; about 0.010% to about 0.050% aluminum; up to about 0.05% niobium; up to about 0.15% residual elements; and the balance iron and incidental impurities.
3. The low carbon alloy steel tube of claim 1, wherein the steel tube consists essentially of, by weight: about 0.08% to about 0.11% carbon; about 1.03% to about 1.18% manganese; about 0.15% to about 0.35% silicon; up to about 0.003% sulfur; up to about 0.012% phosphorous; up to about 0.10% nickel; about 0.63% to about 0.73% chromium; about 0.40% to about 0.45% molybdenum; about 0.03% to about 0.05% vanadium; about 0.025% to about 0.035% titanium; about 0.15% to about 0.30% copper; about 0.010% to about 0.050% aluminum; up to about 0.05% niobium; up to about 0.15% residual elements; and the balance iron and incidental impurities.
4. The low carbon alloy steel tube of claim 1, wherein the steel tube has a yield strength of at least about 125 ksi.

5. The low carbon alloy steel tube of claim 1, wherein the steel tube has a yield strength of at least about 135 ksi
6. The low carbon alloy steel tube of claim 1, wherein the steel tube has an elongation at break of at least about 9%.
7. The low carbon alloy steel tube of claim 1, wherein the steel tube has a hardness of no more than about 40 HRC.
8. The low carbon alloy steel tube of claim 1, wherein the steel tube has a hardness of no more than about 37 HRC.
9. The low carbon alloy steel tube of claim 1, wherein the steel tube has a carbon equivalent of less than about 0.63%, the carbon equivalent being determined according to the formula:
$$C_{eq} = \%C + \%Mn/6 + (\%Cr + \%Mo + \%V)/5 + (\%Ni + \%Cu)/15.$$
10. The low carbon alloy steel tube of claim 9, wherein the steel tube has a carbon equivalent of less than about 0.60%.
11. The low carbon alloy steel tube of claim 9, wherein the steel tube has a carbon equivalent of less than about 0.56%.
12. The low carbon alloy steel tube of claim 1, wherein the steel tube has a maximum microinclusion content of 2 or less --thin series--, and level 1 or less --heavy series--, measured in accordance with ASTM E45 Standard – Worst Field Method (Method A).

13. The low carbon alloy steel tube of claim 1, wherein the steel tube has a maximum microinclusion content measured in accordance with ASTM E45 Standard – Worst Field Method (Method A), as follows:

Inclusion Type	Thin	Heavy
A	0.5	0
B	1.5	1.0
C	0	0
D	1.5	0.5

14. The low carbon alloy steel tube of claim 13, wherein oversize inclusion content with 30 μm or less in size is obtained.

15. The low carbon alloy steel tube of claim 14, wherein the total oxygen content is limited to 20 ppm.

16. The low carbon alloy steel tube of claim 1, wherein the tube has a seamless configuration.

17. A stored gas inflator pressure vessel comprising the low carbon alloy steel tube of claim 1.

18. An automotive airbag inflator comprising the low carbon alloy steel tube of claim 1.

19. A low carbon alloy steel tube consisting essentially of, by weight: about 0.08% to about 0.11% carbon; about 1.03% to about 1.18% manganese; about 0.15% to about 0.35% silicon; up to about 0.003% sulfur; up to about 0.012% phosphorous; up to about 0.10% nickel; about 0.63% to about 0.73% chromium; about 0.40% to about 0.45% molybdenum; about 0.03% to about 0.05% vanadium; about 0.025% to about 0.035% titanium; about 0.15% to about 0.30% copper; about 0.010% to about 0.050% aluminum; up to about 0.05% niobium; up to about 0.15% residual elements; and the balance iron and incidental impurities, wherein the steel tube has a yield strength of at least about 135 ksi, a tensile strength of at least about 145 ksi, an elongation at break of at least about 9%, a hardness of no more than about 37 HRC, and has a ductile-to-brittle transition temperature below -60°C .

20. The low carbon alloy steel tube of claim 19, wherein the tube has a seamless configuration.

21. A stored gas inflator pressure vessel comprising the low carbon alloy steel tube of claim 19.

22. An automotive airbag inflator comprising the low carbon alloy steel tube of claim 19.

23. A method of manufacturing a length of steel tubing for a stored gas inflator pressure vessel, comprising the following steps:

producing a length of tubing from a steel material consisting essentially of, by weight: about 0.06% to about 0.18% carbon, about 0.5% to about 1.5% manganese, about 0.1% to about 0.5% silicon, up to about 0.015% sulfur, up to about 0.025% phosphorous, up to about 0.50% nickel, about 0.1% to about 1.0% chromium, about 0.1% to about 1.0% molybdenum, about 0.01% to about 0.10% vanadium, about 0.01% to about 0.10% titanium, about 0.05% to about 0.35% copper, about 0.010% to about 0.050% aluminum, up to about 0.05% niobium, up to about 0.15% residual elements, and the balance iron and incidental impurities;

subjecting the steel tubing to a cold-drawing process to obtain desired dimensions;

austenizing by heating the cold-drawn steel tubing in an induction-type austenizing furnace to a temperature of at least Ac_3 , at a heating rate of at least about 100°C per second;

after the heating step, quenching the steel tubing in a quenching fluid until the tubing reaches approximately ambient temperature, at a cooling rate of at least about 100 °C per second; and

after the quenching step, tempering the steel tubing for about 2-30 minutes at a temperature below Ac1.

24. The method of claim 23, wherein the steel tubing produced consists essentially of, by weight: about 0.07% to about 0.12% carbon, about 1.00% to about 1.40% manganese, about 0.15% to about 0.35% silicon, up to about 0.010% sulfur, up to about 0.015% phosphorous, up to about 0.20% nickel, about 0.55% to about 0.80% chromium, about 0.30% to about 0.50% molybdenum, about 0.01% to about 0.07% vanadium, about 0.01% to about 0.05% titanium, about 0.15% to about 0.30% copper, about 0.010% to about 0.050% aluminum, up to about 0.05% niobium, up to about 0.15% residual elements, and the balance iron and incidental impurities.

25. The method of claim 23, wherein the steel tubing produced consists essentially of, by weight: about 0.08% to about 0.11% carbon, about 1.03% to about 1.18% manganese, about 0.15% to about 0.35% silicon, up to about 0.003% sulfur, up to about 0.012% phosphorous, up to about 0.10% nickel, about 0.63% to about 0.73% chromium, about 0.40% to about 0.45% molybdenum, about 0.03% to about 0.05% vanadium, about 0.025% to about 0.035% titanium, about 0.15% to about 0.30% copper, about 0.010% to about 0.050% aluminum, up to about 0.05% niobium, up to about 0.15% residual elements, and the balance iron and incidental impurities.

26. The method of claim 23, wherein the finished steel tubing has a yield strength of at least about 125 ksi.

27. The method of claim 23, wherein the finished steel tubing has a yield strength of at least about 135 ksi.

28. The method of claim 23, wherein the finished steel tubing has a tensile strength of at least about 145 ksi.

29. The method of claim 23, wherein the finished steel tubing has an elongation at break of at least about 9%.

30. The method of claim 23, wherein the finished steel tubing has a hardness of no more than about 40 HRC.

31. The method of claim 23, wherein the finished steel tubing has a hardness of no more than about 37 HRC.

32. The method of claim 23, wherein the finished steel tubing has a ductile-to-brittle transition temperature below -60°C .

33. The method of claim 23, wherein in the austenizing heating step, the steel tubing is heated to a temperature between about $920-1050^{\circ}\text{C}$.

34. The method of claim 33, wherein in the austenizing heating step, the steel tubing is heated at a rate of at least about 200°C per second.

35. The method of claim 23, wherein in the quenching step, the steel tubing is cooled at a rate of at least about 200°C per second.

36. The method of claim 23, wherein in the tempering step, the steel tubing is tempered at a temperature between about $400-600^{\circ}\text{C}$.

37. The method of claim 36, wherein in the tempering step, the steel tubing is tempered for about 4-20 minutes.

38. The method of claim 23, further comprising a finishing step wherein the tempered steel tubing is pickled, phosphated, and oiled.

39. A method of manufacturing a length of steel tubing for a stored gas inflator pressure vessel, comprising the following steps:

producing a length of tubing from a steel material consisting essentially of, by weight: about 0.08% to about 0.11% carbon, about 1.03% to about 1.18% manganese, about 0.15% to about 0.35% silicon, up to about 0.003% sulfur, up to about 0.012% phosphorous, up to about 0.10% nickel, about 0.63% to about 0.73% chromium, about 0.40% to about 0.45% molybdenum, about 0.03% to about 0.05% vanadium, about 0.025% to about 0.035% titanium, about 0.15% to about 0.30% copper, about 0.010% to about 0.050% aluminum, up to about 0.05% niobium, up to about 0.15% residual elements, and the balance iron and incidental impurities;

subjecting the steel tubing to a cold-drawing process to obtain desired dimensions;

austenizing by heating the cold-drawn steel tubing in an induction-type austenizing furnace to a temperature between about 920-1050 °C, at a heating rate of at least about 200 °C per second;

after the heating step, quenching the steel tubing in a water-based quenching solution until the tubing reaches approximately ambient temperature, at a cooling rate of at least about 200 °C per second; and

after the quenching step, tempering the steel tubing for about 4-20 minutes at a temperature between about 450-550 °C,

a finishing step wherein the tempered steel tubing is pickled, phosphated, and oiled,

wherein the finished steel tubing has a yield strength of at least about 135 ksi, a tensile strength of at least about 145 ksi, an elongation at break of at least about 9%, a hardness of no more than about 37 HRC, a ductile-to-brittle transition temperature below -60 °C and a good surface appearance.

INTERNATIONAL SEARCH REPORT

International Application No
/IB2004/003311

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 C21D8/10 C21D9/08 C22C38/00 C22C38/20 C22C38/22
C22C38/24

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 C21D C22C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ, WPI Data, CHEM ABS Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2003/155052 A1 (BEPPU KENICHI ET AL) 21 August 2003 (2003-08-21) paragraphs '0079!', '0081! - '0089! page 6 - page 7; example e; tables 2,3 paragraphs '0105!', '0107! claims 1-15	1-39
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Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

° Special categories of cited documents :

- *A* document defining the general state of the art which is not considered to be of particular relevance
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20 January 2005

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INTERNATIONAL SEARCH REPORT

International Application No

IB2004/003311

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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