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[54] METHOD OF PRODUCING ROLLED STEEL HAVING HIGH STRENGTH AND LOW IMPACT TRANSITION TEMPERATURE

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Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 741,372, June 27, 1968, abandoned.

[52] **U.S. Cl.** 148/12

[51] **Int. Cl.** C21d 7/14, C21d 9/46

[58] **Field of Search** 148/12, 12.4

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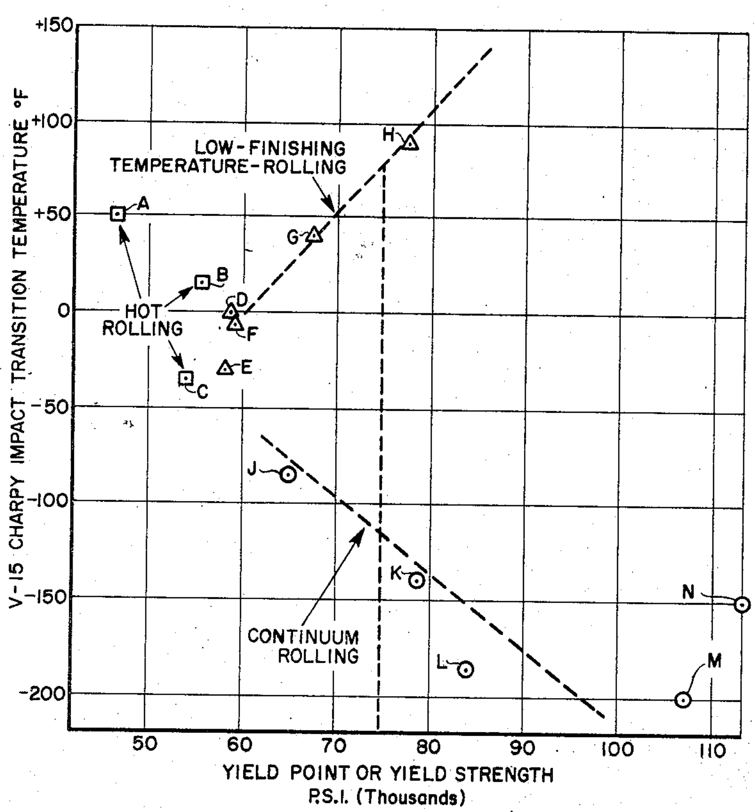
[57] **ABSTRACT**

Rolled steels characterized in their as-rolled condition by an unexpected combination of high-strength and low-impact transition temperature. The product is produced by rolling a steel workpiece containing both austenite and ferrite, preventing complete recrystallization at any time thereafter, and continuing the rolling of said workpiece as it is cooling in the temperature range between the Ar_1 temperature and 600° F.

4 Claims, 3 Drawing Figures



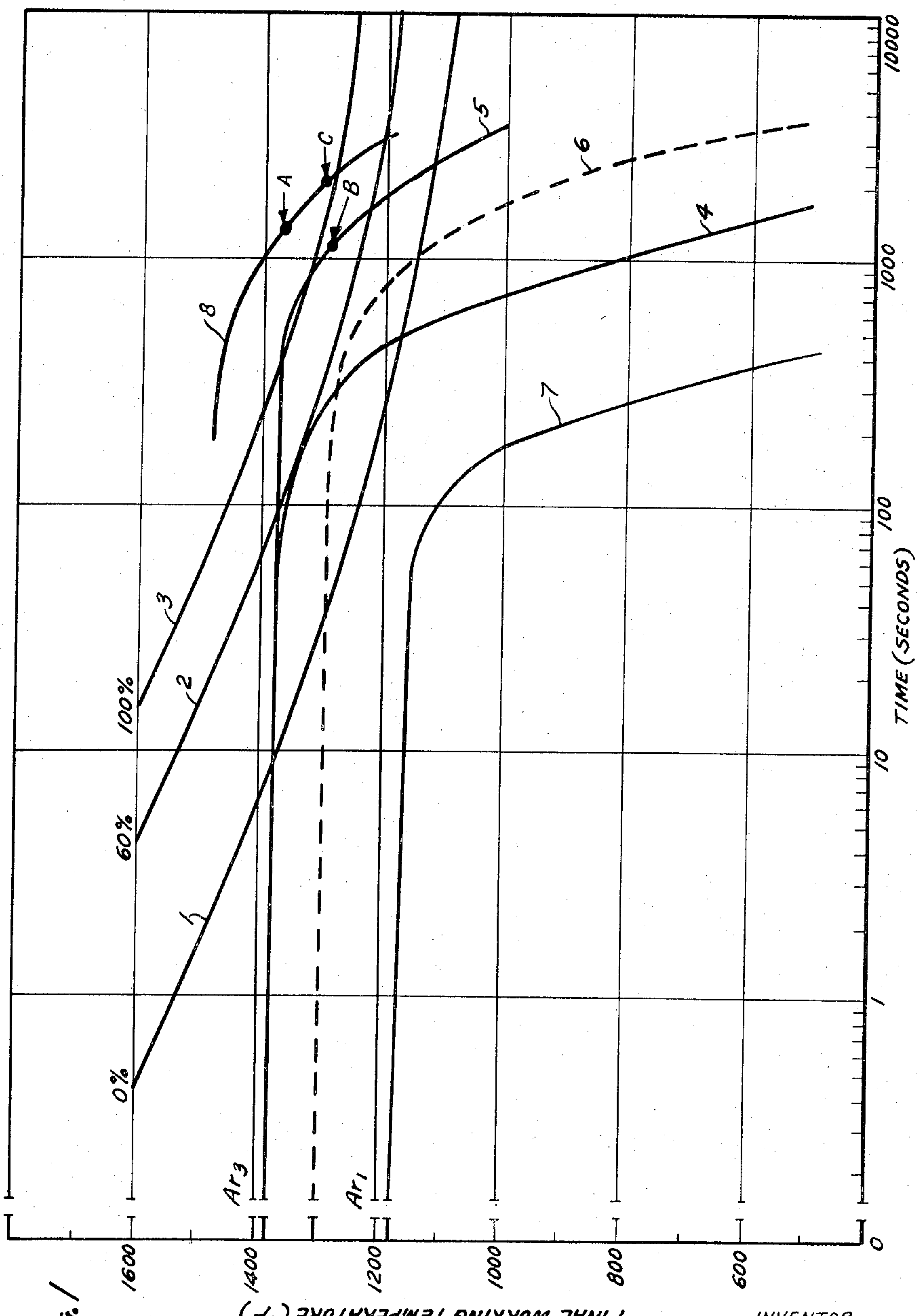


FIG. 1

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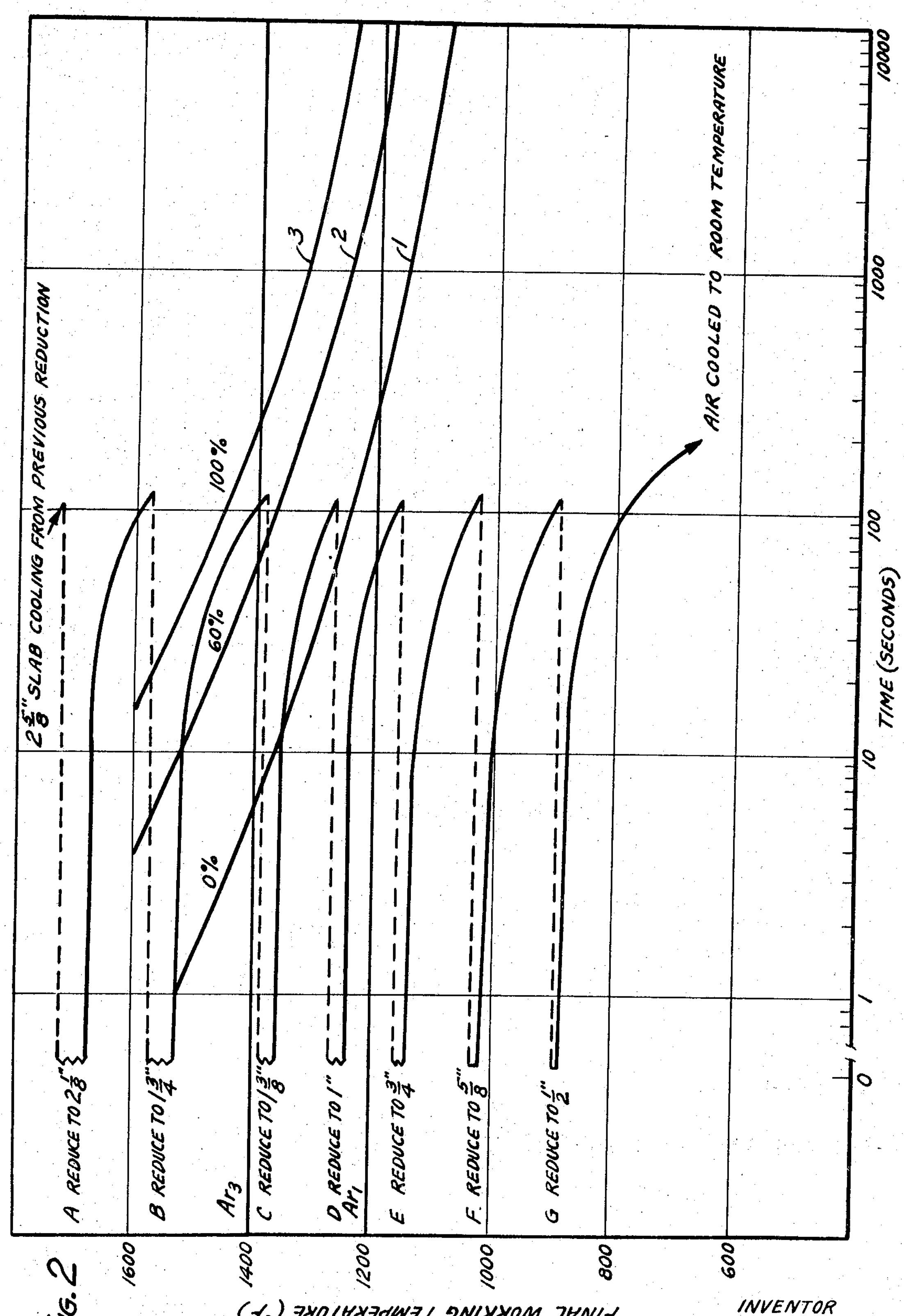

FIG. 2

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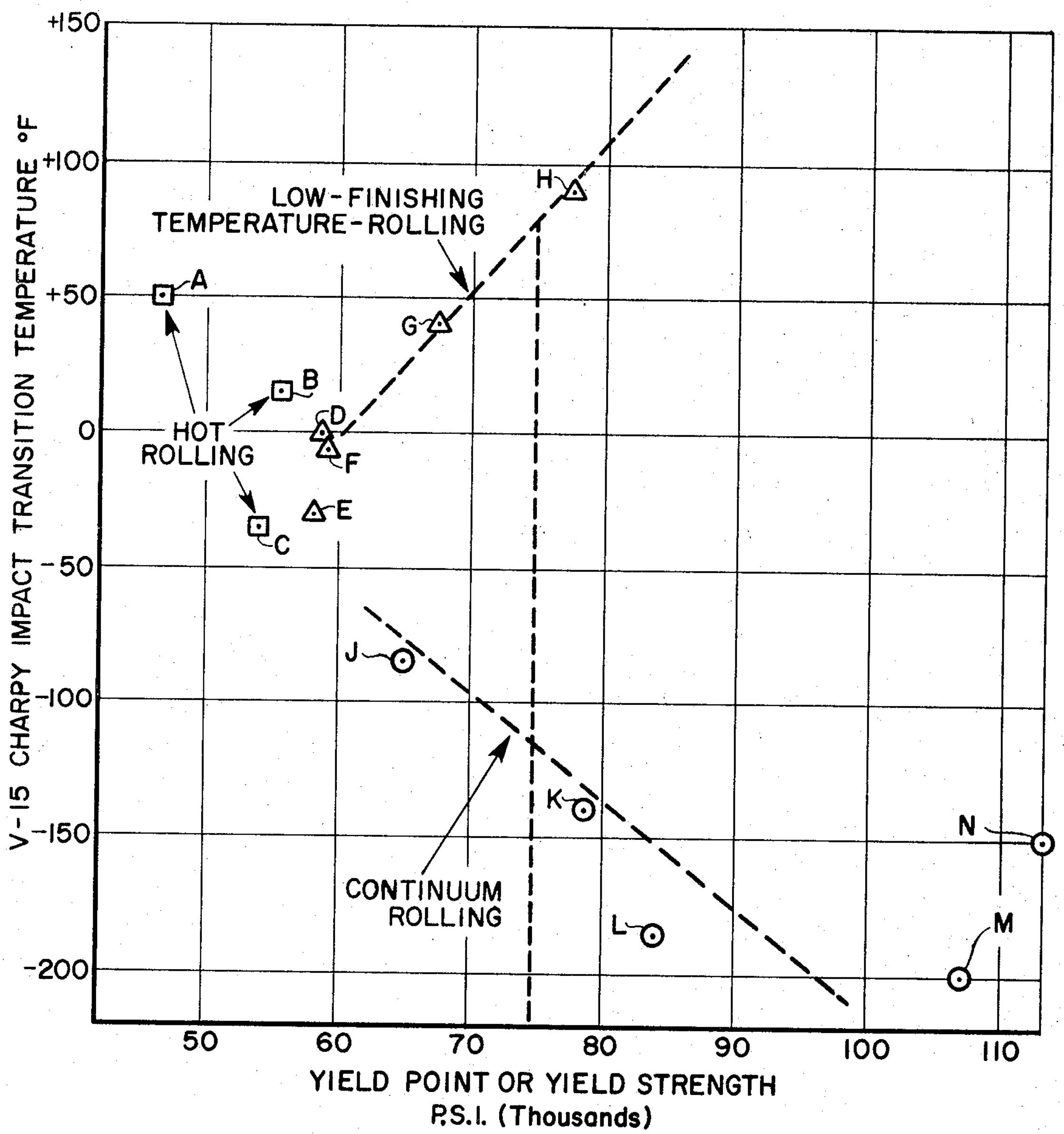
Fig. 3



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METHOD OF PRODUCING ROLLED STEEL HAVING HIGH-STRENGTH AND LOW-IMPACT TRANSITION TEMPERATURE

CROSS-REFERENCES TO RELATED APPLICATIONS

This application is a continuation-in-part of application Ser. No. 741,372, filed June 27, 1968 and now abandoned.

BACKGROUND OF THE INVENTION

This invention is directed to rolled steel and a method of producing the same. For convenience, the method is sometimes hereinafter called "continuum rolling."

Normal practice used to produce hot-rolled steel consists of heating the steel to a temperature at which it is fully austenitic and then reducing the steel to final dimensions as rapidly as possible with a minimum of heat loss, generally finishing above the Ar_3 temperature. Such practice takes advance of ease of working at high temperature, but does not develop the combination of desirable properties possible of development in as-rolled steel.

Prior studies have shown that higher strength can be developed in the steel by use of low-finishing-temperature rolling. In this practice, the steel is heated and partially reduced while austenitic, as in hot rolling. Further reduction of the cross section is then delayed to allow the workpiece to cool to a lower-than-normal temperature after which rolling is continued to the final desired cross section in one or more passes.

In these prior art practices, the cross-sectional area of the workpiece is reduced to final size and shape in a sequence of rolling passes. Such passes may include two general types, those intended mainly to reduce the cross-sectional area of the workpiece and those intended mainly for gage or shape and which may be accompanied by relatively little reduction. As a matter of economy, a rolling sequence should comprise a few passes as possible or practical. Each pass intended primarily for reduction should therefore effect as great a reduction in cross-sectional area as possible or practical. Further, it is known that development of the aforementioned higher strength by low-finishing-temperature rolling requires reduction of cross-sectional area of approximately 15 percent or more at the lower-than-normal temperature.

In low-finishing-temperature rolling, it is known that the steel is strengthened and its impact transition temperature is decreased by lowering the finishing temperature below the Ar_3 temperature. It is also known that further strengthening is obtained by further lowering the finishing temperature below the Ar_1 temperature, but impact transition temperature is thereby increased. In contrast, we have found that by use of continuum rolling, such further strengthening is accompanied by a decrease rather than an increase in impact transition temperature. This combination of high strength and low impact transition temperature is an unexpected and very desirable combination of properties.

SUMMARY OF THE INVENTION

The steels of this invention are characterized in their as-rolled condition (a) by having greater strengths and lower impact transition temperatures than steels of the same composition produced by hot rolling and (b) by having lower impact transition temperatures than steels of the same composition produced to the same strength by low-finishing-temperature rolling.

Broadly, the method of this invention comprises:

1. providing a steel workpiece at a temperature at which it is essentially completely austenitic,
2. rolling said workpiece as it is cooling in the temperature range between the Ar_3 and Ar_1 temperatures,
3. continuing the rolling of said workpiece as it is cooling in the temperature range between the Ar_1 temperature and 600° F., and
4. preventing complete recrystallization at any time after completion of step 2.

The benefits of the invention are primarily applicable to steels containing not more than 0.35 percent carbon and not more than a total of 3 percent of other elements other than iron.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram showing the relationship between typical cooling curves of steel plates and curves representing various percentages of recrystallization.

FIG. **2** shows a possible continuum rolling sequence superimposed on a recrystallization diagram similar to FIG. **1**.

FIG. **3** is a graph comparing impact transition temperatures and yield points or yield strengths of steel of a particular composition produced by continuum rolling with those of steel of the same composition produced by (1) hot rolling and (2) low-finishing-temperature rolling.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The method of this invention differs from prior art methods in that (a) the steel must be rolled in two temperature ranges, namely, between the Ar_3 and the Ar_1 temperatures and between the Ar_1 temperature and 600° F. and preferably in three temperature ranges, namely, the two first-mentioned temperature ranges and the hot-rolling temperature range and (b) complete recrystallization at any time after completion of the rolling in the Ar_3–Ar_1 temperature range must be avoided.

The workpiece for rolling in the Ar_3–Ar_1 temperature range is a steel workpiece at a temperature at which it is essentially completely austenitic. Various methods of obtaining said workpiece will be recognized by those skilled in the art but preferably said workpiece is obtained by hot rolling. The amount of reduction in such hot rolling is not critical, but from a practical viewpoint it is helpful to take as much reduction as possible because of ease of working. Such rolling in the Ar_3–Ar temperature range must be carried out as the workpiece is cooling in that range and must comprise one or more rolling passes including at least one reduction pass. The meaning of the term "reduction pass," as used herein, encompasses both a single pass in which the reduction of the cross-sectional area of the workpiece is at least 15 percent and two or more passes effecting an amount of reduction and taken in rapid enough succession to prevent any recrystallization between passes.

Following the rolling in the Ar_3–Ar_1 temperature range, rolling must be continued as the workpiece is cooling in the Ar_1-600° F. temperature range and must comprise one or more rolling passes in that range including at least one reduction pass.

Conditions following the rolling in the Ar_3–Ar_1 temperature range must be such that complete recrystallization of the deformed grains produced by the last reduction pass in said temperature range does not take place at any time after such last reduction pass and preferably such that percentage recrystallization does not exceed 60 percent at any time after such last reduction pass.

As used herein, percentage recrystallization means the cross-sectional area of recrystallized grains expressed as a percentage of total cross-sectional area on a plane transverse to the direction of maximum elongation of the workpiece during rolling.

FIG. **1** illustrates diagrammatically the principles upon which reduction in the Ar_3–Ar_1 range and in the Ar_1-600° F. range depend. In the FIGURE, the abscissa represents time on a logarithmic scale with zero time representing the time at completion of a reduction pass. The ordinate represents temperature, with the Ar_3 and Ar_1 temperatures indicated. Lines **1**, **2**, and **3** represent, respectively, times and temperatures for commencement of, 60 percent and 100 percent recrystallization. Lines **4**, **5**, **6**, **7**, and **8** represent the cooling of steel workpieces. It will be understood that the values shown in the FIGURE are illustrative only; actual values depend on the actual workpieces being considered and can be determined by known methods.

As stated hereinabove, it is necessary to roll the workpiece in the Ar_3–Ar_1 range and to follow such rolling by rolling in the Ar_1-600° F. range while maintaining conditions such that complete recrystallization is avoided and preferably such that recrystallization does not exceed 60 percent at any time after completion of the last reduction pass in the first-mentioned rolling. In the FIGURE, Point A on Line **8** indicates a temperature to which a steel workpiece has cooled and which is within the Ar_3–Ar_1 range. Line **5** represents the cooling of said workpiece after it has been given a reduction pass at the temperature represented by Point A. It will be seen that as said reduced workpiece cools along Line **5**, it completely recrystallizes before it cools to a temperature below the Ar_1 temperature, thus becoming unsuitable for the subsequent reduction in the Ar_1-600° F. range. There are ways of meeting this situation. One way is to accelerate the cooling of said reduced workpiece by water sprays, air blasts or the like so that it cools to a temperature below the Ar_1 temperature while avoiding complete recrystallization, as shown for example by Line **4**. A second way is to allow said reduced workpiece to cool as shown by Line **5** to a temperature as indicated for example by Point B and then to give it a second reduction pass within the Ar_3–Ar range. As shown by Line **6**, such twice-reduced workpiece cools to a temperature below the Ar_1 temperature with less than 60 percent recrystallization. A third way is to allow the aforementioned workpiece of Line **8** to cool to a lower temperature, as indicated for example by Point C, and then to give it a reduction pass within the Ar_3–Ar_1 range. The cooling of such reduced workpiece is also shown by Line **6**.

As stated hereinabove, complete recrystallization of the steel at any time after the last reduction pass in the Ar_3–Ar_1 range must be prevented. In FIG. **1**, Line **7** represents the cooling of a steel workpiece after a reduction pass at a temperature below the Ar_1 temperature. It is seen that recrystallization is avoided as such reduced workpiece cools. However, if the temperature at which a reduction pass is effected and the cooling and recrystallization characteristics of the resulting reduced workpiece are such that it would recrystallize before being given another reduction pass or before cooling to a temperature sufficiently low to prevent recrystallization, then the cooling of said reduced workpiece must be accelerated by water sprays, air blasts of the like so as to prevent complete recrystallization and preferably so as to prevent exceeding 60 percent recrystallization.

FIG. **2** illustrates diagrammatically a possible rolling sequence for producing a ½-inch plate by continuum rolling. In the FIGURE the abscissa represents time on a logarithmic scale, with zero time representing the time at completion of a reduction pass. The ordinate represents temperature on an arithmetic scale, with Ar_3 and Ar_1 temperatures indicated. Lines **1–3** represent times and temperatures for commencement of, 60 percent, and 100 percent recrystallization. The horizontal dashed lines represent instantaneous return to zero time. In this example, a 2⅝-inch slab has been rolled from A 4-inch slab at temperatures well above the Ar_3 temperature and, as shown in the FIGURE, has air cooled in about 2 minutes to about 1,720° F. This 2⅝-inch slab is given two passes at temperatures above the Ar_3 temperature, first to 2⅛ inches (A) and then 1¾ inches (B). After each of these passes the plate cools in air for about 2 minutes, cooling during the latter period to about 1,385° F., somewhat below the Ar_3 temperature.

In the Ar_3–Ar_1 temperature range the steel is given two passes, first to 1⅜ inches (C) and then to 1 inch (D). After each of these passes the plate cools in air for about 2 minutes, cooling during the latter period to about 1,160° F., somewhat below the Ar_1 temperature. Percentage recrystallization following the first pass is small, and there is no recrystallization following the second pass.

In the temperature range between the Ar_1 temperature and 600° F. the steel is given three passes, first to ¾ inch (E), then to ⅝ inch (F), and finally to ½ inch (G). After each of the first two of these passes to the plate cools in air for about 2 minutes; after the final pass, the plate cools in air to room temperature. There is no recrystallization following any of these passes.

All of the passes in this rolling sequence are reduction passes and it is to be understood that such other passes as may be necessary can be included provided that percentage recrystallization is controlled as hereinabove described. Also, the cooling periods of about two minutes in air were chosen as a matter of convenience and it is to be understood that percentage recrystallization can be controlled with different cooling periods and different cooling methods as hereinabove described.

Following are descriptions of specific examples of plates produced by continuum rolling and by prior art methods.

Thirteen plates were made of steel having the following nominal percentage composition:

C	Mn	P	S	Si	Al	Cb	N_2
0.052	1.08	0.01	0.015	0.02	0.005	0.03	0.002

balance substantially iron.

4-inch thick slabs of this steel were heated to a temperature of 2,200° F. and rolled to ½-inch plate in accordance with the following schedule:

Pass No.	Thickness after Each Pass	Reduction in Thickness
1	3½''	12.5%
2	3''	16.7%
3	3''*	—
4	2⅝''	12.5%
5	2⅛''	19.1%
6	1¾''	17.6%
7	1⅜''	21.4%
8	1''	27.2%
9	¾''	25.0%
10	⅝''	16.7%
11	½''	20.0%

* Box pass to obtain width.

The Ar_3 and Ar_1 temperatures of this steel were 1,500° F. and 1,320° F. respectively at a cooling rate of approximately 1,000° F./hr.

Table 1 shows the temperature ranges in which the above reduction schedule was carried out. Plates A–H are illustrative of plates produced by prior art rolling methods, while Plates J–N are illustrative of plates produced by continuum rolling. The recrystallization characteristics of the steel and the cooling rates and intervals between passes were such that in the rolling of Plates J–N the percentage recrystallization did not exceed 60 percent at any time after completion of the reduction in the Ar_3–Ar_1 temperature range.

Table 2 shows the finishing temperature, yield point or yield strength, tensile strength, elongation, and V-15 Charpy impact transition temperature of each of the thirteen plates A–N.

FIG. 3 shows for the said 13 plates the manner in which impact transition temperature varies with strength as dependent on the method of rolling. In the FIGURE, points A, B, and C represent plates produced by hot rolling, points D and E represent plates finished at temperatures between the Ar_3 and the Ar_1 temperatures by low-finishing-temperature rolling, points F, G, and H represents plates finished at temperatures below the Ar_1 temperature by low-finishing-temperature rolling, and points J, K, L, M, and N represent plates produced by continuum rolling. Both the FIGURE and Table 2 show clearly that the plates produced by continuum rolling have higher strengths and lower impact transition temperatures than do those produced by hot rolling. Moreover, Table 2 shows clearly that finishing the rolling at temperatures below the Ar_1 temperature either by low-finishing-temperature rolling or by continuum rolling increased the strength of the steel over that obtained by finishing the rolling at temperatures above the Ar_1 temperature. However, the important distinction shown by both the TABLE and the FIGURE is that when such further strengthening is by low-finishing-temperature rolling impact transition temperature is raised as strength is increased, whereas when such further strengthening is by continuum rolling impact transition temperature is lowered as strength is increased. The difference is substantial. For example, the dashed lines on the FIGURE show that low-finishing-temperature rolling could provide a plate with a yield strength of 75,000 p.s.i. and an impact transition temperature of approximately plus 80° F., whereas continuum rolling could provide a plate of the same strength with an impact transition temperature nearly 200° lower, namely, approximately minus 115° F.

Table 3 gives the percentage compositions of seven other steels from which specific examples of plates were produced by continuum rolling and by prior art methods. In each of these steels the balance of the composition was substantially iron. Varieties included are semikilled, killed, carbon, low alloy, bainitic, and precipitation hardening steels.

The Ar_3 and Ar_1 temperatures of the Table 3 steels at cooling rates of approximately 1,000° F./hr. are shown in Table 4.

Table 4

No.	Ar_3	Ar_1
1	1520° F.	1400° F.
2	1520° F.	1320° F.
3	1500° F.	1300° F.
4	1440° F.	1220° F.
5	1400° F.	1200° F.
6	1400° F.	1160° F.
7	1140° F.	960° F.

One or more slabs of each of the compositions specified in Table 3 were rolled to ½-inch plate by continuum rolling. For comparative purposes, one or more slabs of each composition were also rolled into ½-inch plate by prior art rolling methods. The details of the rolling practices, and the resulting yield strengths or yield points, tensile strengths, and V-15 Charpy impact transition temperatures are set forth in Tables 5–11.

In reference to the data set forth in Tables 5–11, it is well **known that the strength and impact transition temperature of a steel are affected both by the composition of the steel and by the way in which it is processed. For example, Tables 5–11** show a wide range of strengths and impact transition temperatures for steels of seven different compositions each of which was rolled by prior art methods and by one or more examples of continuum rolling, while Table 2 shows a wide range of strengths and impact transition temperatures for a steel of a particular composition rolled in a number of ways, including several different examples of continuum rolling. Every plate produced by continuum rolling has an unexpectedly good combination of strength and impact transition temperature, but for the reason cited above it is not possible to broadly characterize the product of continuum rolling in terms of specific values of those properties. As said earlier, the products of continuum rolling are characterized in their as-rolled condition (a) by having greater strengths and lower impact transition temperatures than steels of the same composition produced by hot-rolling and (b) by having lower impact transition temperatures than steels of the same compositions produced to the same strength by low-finishing-temperature rolling.

Although the method of this invention has been described only in connection with the rolling of plates, the method may be used in the rolling of other products such as billets, bars, structural sections and the like.

All references herein to steel compositions in terms of percentages are weight percentages.

TABLE 1

Plate	Number of passes	Temperature range, ° F.	Reduction in thickness, inches: From	Reduction in thickness, inches: To	Reduction, percent
Hot rolling					
A	11	2,200–1,840	4	1/2	87.5
B	11	2,200–1,720	4	1/2	87.5
C	11	2,200–1,530	4	1/2	87.5
Low-finishing-temperature rolling					
D	10	2,200–1,800	4	5/8	84.3
	1	1,490	5/8	1/2	20.0
E	8	2,200–1,500	4	1	75.0
	3	1,500–1,405	1	1/2	50.0
F	10	2,200–1,800	4	5/8	84.3
	1	1,310	5/8	1/2	20.0
G	10	2,200–1,800	4	5/8	84.3
	1	1,130	5/8	1/2	20.0
H	10	2,200–1,800	4	5/8	84.3
	1	910	5/8	1/2	20.0
Continuum rolling					
J	7	2,200–1,500	4	1-3/8	65.6
	2	1,500–1,320	1-3/8	3/4	45.4
	2	1,320–1,205	3/4	1/2	33.3
K	6	2,200–1,500	4	1-3/4	56.2
	2	1,500–1,320	1-3/4	1	42.8
	3	1,320–1,080	1	1/2	50.0
L	5	2,200–1,500	4	2-1/8	46.8
	2	1,500–1,320	2-1/8	1-3/8	35.3
	4	1,320–900	1-3/8	1/2	63.6
M	4	2,200–1,500	4	2-5/8	34.4
	2	1,500–1,320	2-5/8	1-3/4	33.3
	5	1,320–730	1-3/4	1/2	71.5
N	4	2,200–1,500	4	2-5/8	34.4
	2	1,500–1,320	2-5/8	1-3/4	33.3
	5	1,320–625	1-3/4	1/2	71.5

TABLE 2

Plate	Finishing temperature, ° F.	Yield point, p.s.i.	Tensile strength, p.s.i.	Percent elongation: 2 inch	Percent elongation: 8 inch	V-15 charpy impact transition temperature, ° F.
Hot rolling						
A	1,840	46,400	66,000	--------	21	+50
B	1,720	55,700	68,000	--------	21	+15
C	1,530	53,900	61,700	--------	24	−35
Low-finishing-temperature rolling						
D	1,490	58,500	69,300	38	--------	0
E	1,405	58,100	64,300	--------	24	−30
F	1,310	59,500	74,300	31	--------	−5
G	1,130	*67,100	76,100	26	--------	+40
H	910	*77,500	83,600	25	--------	+90
Continuum rolling						
J	1,205	65,100	71,200	--------	18	−85
K	1,080	*78,500	83,400	26	14	−140
L	900	*84,000	86,700	23	10	−185
M	730	*107,600	107,800	16	--------	−200
N	625	*113,100	113,700	15	--------	−150

*Yield strength (0.2% offset).

TABLE 3

Number	Type	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Al	V	Cb	B	N
		Composition (percent)													
1	Very low C-Mn-V	.002	1.06	.009	.018	.02	.01	.01	.008	.01	<.005	.06	Nil	Nil	.002
2	Low C-Mn	.051	0.13	.008	.015	.02	.02	.01	.002	.01	<.005	.002	Nil	Nil	.001
3	Low C-Mn-V-N	.050	1.08	.009	.015	.02	.03	.01	.008	.01	<.005	.07	Nil	Nil	.008
4	Low alloy	.10	.69	.083	.025	.30	.71	.57	Nil	.24	<.005	.003	Nil	Nil	.007
5	C-Mn	.28	1.11	.020	.032	.20	.03	.04	Nil	.05	.043	.002	Nil	Nil	.005
6	1% copper	.24	1.08	.014	.015	.33	.02	.01	Nil	1.00	.079	.003	Nil	Nil	.008
7	Bainitic	.12	1.05	.011	.014	.26	.04	.50	.50	.02	.039	.003	Nil	.003	.007

TABLE 5

[Steel No. 1—Very low C-Mn-V]

Reduction practice	Number of passes	Temperature range, ° F.	Thickness, inches	Reduction, percent	Yield point, K s.i.	Tensile strength, K s.i.	V-15 Charpy transition temperature, ° F.
Hot rolling	11	2,200–1,710	4"→1/2"	87.5	27.0	43.4	+5
Do	11	2,200–1,550	4"→1/2"	87.5	24.0	42.1	+20
Continuum rolling	4	2,200–1,520	4"→2 5/8"	34.4			
	2	1,520–1,400	2 5/8"→1 3/4"	33.3			
	5	1,400–880	1 3/4"→1/2"	71.5	*62.0	69.3	−260

*Yield strength (0.2% offset).

TABLE 6

[Steel No. 2—Low C-Mn]

Reduction practice	Number of passes	Temperature range, ° F.	Thickness, inches	Reduction, percent	Yield point, K s.i.	Tensile strength, K s.i.	V-15 Charpy transition temperature, ° F.
Hot rolling	11	2,200–1,700	4"→1/2"	87.5	32.4	49.4	−10
Continuum rolling	6	2,200–1,520	4"→1 3/4"	56.2			
	2	1,520–1,320	1 3/4"→1"	42.8			
	2	1,320–1,100	1"→1/2"	50.0	*63.7	74.4	−110
Do	4	2,200–1,520	4"→2 5/8"	34.4			
	2	1,520–1,320	2 5/8"→1 3/4"	33.3			
	5	1,320–890	1 3/4"→1/2"	71.5	*69.2	77.2	−285

*Yield strength (0.2% offset).

TABLE 7

[Steel No. 3—Low C-Mn-V-N]

Reduction practice	Number of passes	Temperature range, ° F.	Thickness, inches	Reduction, percent	Yield point, K s.i.	Tensile strength, K s.i.	V-15 Charpy transition temperature, ° F.
Hot rolling	11	2,200–1,610	4"→1/2"	87.5	49.3	61.9	−25
Do	10	2,200–1,505	4"→1/2"	87.5	55.0	62.1	−55
Continuum rolling	6	2,200–1,500	4"→1 3/4"	56.2			
	2	1,500–1,300	1 3/4"→1"	42.8			
	2	1,300–1,205	1"→1/2"	50.0	*71.6	76.5	−185

*Yield strength (0.2% offset).

TABLE 8

[Steel No. 4—Low alloy]

Reduction practice	Number of passes	Temperature range, ° F.	Thickness, inches	Reduction, percent	Yield point, K s.i.	Tensile strength, K s.i.	V-15 Charpy transition temperature, ° F.
Hot rolling	11	2,200–1,700	5"→1/2"	90.0	51.7	72.5	−10
Do	11	2,200–1,490	5"→1/2"	90.0	56.5	73.5	−70
Low-finishing-temperature rolling	10	2,200–1,850	5"→5/8"	87.5			
	1	1,320	5/8"→1/2"	20.0	59.4	77.2	−20
Continuum rolling	5	2,200–1,450	5"→2 1/8"	57.5			
	3	1,440–1,220	2 1/8"→.830"	61.0			
	1	1,110	.830"→1/2"	39.8	*93.5	98.6	−200

*Yield strength (0.2% offset).

TABLE 9

[Steel No. 5—C-Mn (killed)]

Reduction practice	Number of passes	Temperature range, ° F.	Thickness, inches	Reduction, percent	Yield point, K s.i.	Tensile strength, K s.i.	V-15 Charpy transition temperature, ° F.
Hot rolling	11	2,200–1,740	6"→1/2"	91.7	48.5	76.1	−35
Do	9	2,200–1,500	6"→1/2"	91.7	53.5	76.9	−55
Low-Finishing-Temperature Rolling.	10	2,200–1,850	6"→5/8"	89.5			
	1	1,310	5/8"→1/2"	20.0	54.7	78.9	−5
Continuum rolling	5	2,200–1,400	6"→2 1/8"	64.6			
	2	1,400–1,200	2 1/8"→1 3/8"	35.3			
	2	1,200–1,100	1 3/8"→1/2"	63.6	*88.1	96.6	−180

*Yield strength (0.2% offset).

TABLE 10

[Steel No. 6—1% copper]

Reduction practice	Number of passes	Temperature range, ° F.	Thickness, inches	Reduction, percent	Yield point, K s.i.	Tensile strength, K s.i.	V-15 Charpy transition temperature, ° F.
Hot rolling	11	2,200–1,650	4"→1/2"	87.5	60.6	91.7	+20
Continuum rolling	5	2,200–1,400	4"→2 1/8"	46.8			
	3	1,400–1,160	2 1/8"→1"	53.0			
	3	1,160–940	1"→1/2"	50.0	*107.8	119.1	−185

*Yield strength (0.2% offset).

TABLE 11

[Steel No. 7—Bainitic]

Reduction practice	Number of passes	Temperature range, ° F.	Thickness, inches	Reduction, percent	Yield point, K s.i.	Tensile strength, K s.i.	V-15 Charpy transition temperature, ° F.
Hot rolling	10	2,200-1,500	4"→½"	87.5	41.1	79.2	−5
Do	10	2,200-1,360	4"→½"	87.5	39.4	84.6	−75
Continuum rolling	7	2,200-1,140	4"→1⅜"	65.6			
	2	1,140-960	1⅜"→.830"	39.6			
	1	920	.830"→½"	39.8	* 98.4	116.9	−205

*Yield strength (0.2% offset).

We claim:

1. Method of rolling a steel workpiece containing not more than 0.35 percent carbon and not more than a total of 3 percent of other elements other than iron comprising:

a. rolling said workpiece in one or more passes as it is cooling from a temperature at which it is austenitic but while its temperature is still above the Ar_3 temperature,

b. continuing the rolling of said workpiece in one or more passes including at least one reduction pass as it is cooling in the temperature range between the Ar_3 and the Ar_1 temperatures,

c. continuing the rolling of said workpiece in one or more passes including at least one reduction pass as it is cooling in the temperature range between the Ar_1 temperature and 600° F., and

d. maintaining conditions such that complete recrystallization does not take place at any time after the last reduction pass in step (b).

2. Method of rolling a steel workpiece containing not more than 0.35 percent carbon and not more than a total of 3 percent of other elements other than iron comprising:

a. rolling said workpiece in one or more passes as it is cooling from a temperature at which it is austenitic but while its temperature is still above the Ar_3 temperature,

b. continuing the rolling of said workpiece in one or more passes including at least one reduction pass as it is cooling in the temperature range between the Ar_3 and the Ar_1 temperatures,

c. continuing the rolling of said workpiece in one or more passes including at least one reduction pass as it is cooling in the temperature range between the Ar_1 temperature and 600° F., and

d. maintaining conditions such that the percentage recrystallization does not exceed 60 percent at any time after the last reduction pass in step (b).

3. Method of rolling a steel workpiece containing not more than 0.35 percent carbon and not more than a total of 3 percent of other elements other than iron comprising:

a. providing said workpiece at a temperature at which it is essentially completely austenitic,

b. rolling said workpiece in one or more passes including at least one reduction pass as it is cooling in the temperature range between the Ar_3 and the Ar_1 temperatures,

c. continuing the rolling of said workpiece in one or more passes including at least one reduction pass as it is cooling in the temperature range between the Ar_1 temperature and 600° F., and

d. maintaining conditions such that complete recrystallization does not take place at any time after the last reduction pass in step (b).

4. Method of rolling a steel workpiece containing not more than 0.35 percent carbon and not more than a total of 3 percent of other elements other than iron comprising:

a. providing said workpiece at a temperature at which it is essentially completely austenitic,

b, rolling said workpiece in one or more passes including at least one reduction pass as it is cooling in the temperature range between the Ar_3 and the Ar_1 temperatures,

c. continuing the rolling of said workpiece in one or more passes inclu;ing at least one reduction pass as it is cooling in the temperature range between the Ar_1 temperature and 600° F., and

d. maintaining conditions such that the percentage recrystallization does not exceed 60 percent at any time after the last reduction pass in step (b).

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