MEEN 160

MATERIALS SELECTION IN MECHANICAL DESIGN

EXPERIMENT #8

HARDENABILITY AND THE SELECTION OF MEDIUM CARBON STEELS

by

Minster

I. INTRODUCTION

The maximum diameter of a steel rod which can be through hardened or the depth to which it can be hardened under given quenching conditions is defined to be its hardenability. The hardenability of a steel can be quantitatively described by its critical diameter Do, which is the diameter of steel rod which will harden to a minimum of 50% martensite at its center when quenched in a quench of some quench severity factor, H. This diameter is mathematically related to a so-called ideal critical diameter, D_I, which is the diameter of steel rod which will harden to a minimum of 50% martensite at its center when quenched in an ideal quench in which the steel rod is brought immediately to the quenchant temperature and held there. This ideal critical diameter is related to the Jominy distance, J, the distance from the quenched end of a standard 1.0 inch diameter Jominy end quench specimen to a point at which a minimum of 50% martensite is found. In this experiment the Jominy hardenability of AISI/SAE 8620, 1045, 4340, 4130 and 6150 steel was determined experimentally and compared with curves theoretically calculated from the composition limits of the steels. The microstructure along the bar was also characterized in order to explain the hardness changes along the lengths of the bars.

II. PROCEDURE

A Jominy end quench specimen of AISI/SAE 8620, 1045, 4340, 4130 and 6150 steel was studied in this experiment. The relevant concentration limits for the alloy elements present were identified and recorded on the group data sheet. Before lab the TA austenitized the Jominy bar at 900°C for one hour under a neutral atmosphere in an atmosphere furnace. After one hour, the Jominy bar was immediately quenched in the Jominy quenching rig. When the quenching process was complete, the sample was brought down to the discovery learning center where an engineer ground two flats on opposite sides of the bar. Next, the R_C hardness reading were taken along both sides of the bar using the Equitron fixture, One sixteenth inch intervals were used between reading for the first inch from the quenched end. Then, $1/8^{th}$ inch intervals were used for the second inch, and lastly $1/4^{th}$ inch intervals were marked for the remainder of the bar. All of the values were recorded in the group data sheet. One side of the specimen was ground, polished, and etched (with 3% Nital), so the microstructure along the length of the bar could be observed. The changes in the microstructure were denoted and how they correlate with the hardness changed along the bar was observed. The ASTM austenite grain size of the bar was determined and recorded.

III. RESULTS

a. Data

Table 1. Steel Composition limit in weight percent

Jominy Spec. Nos.	AISI/SAE No.	Alloy Element						
		Fe	C	Mn	Si	Cr	Mo	Ni
1-3	8620	Bal.	0.18/0.23	0.70/0.90	0.15/0.35	0.40/0.70	0.15/0.25	0.40/0.70
4-6	4130	Bal.	0.28/0.33	0.40/0.60	0.15/0.35	0.80/1.10	0.15/0.25	-
7-9	4140	Bal.	0.38/0.43	0.75/1.00	0.15/0.35	0.80/1.10	0.15/0.25	-
10-12	4340	Bal.	0.38/0.43	0.60/0.80	0.15/0.35	0.70/0.90	020/0.30	1.65/2.00
13-15	6150*	Bal.	0.48/0.53	0.70/0.90	0.15/0.35	0.80/1.10	-	-
16-18	1045	Bal.	0.43/0.50	0.60/0.90	0.10/0.25	-	-	-

Table 2-a. Experimental Jominy Hardness Profile data for AISI/SAE 8620 Steel

Interval	Specimen #1		Specimen #2		Specimen #3	
(inch)	Side 1	Side 2	Side 1	Side 2	Side 1	Side 2
1/16	45.4	42.4	45.4	43.1	44.3	42.8
1/8	43.8	43.3	42.8	43.2	43.6	44.1
3/16	42.0	41.0	40.0	39.5	40.7	40.0
1/4	36.8	37.2	33.1	32.7	34.0	34.7
5/16	32.6	28.7	28.9	29.1	30.6	31.1
3/8	29.3	26.8	27.5	26.7	25.9	26.5
7/16	26.5	26.8	23.5	25.1	25.2	25.3
1/2	23.9	25.0	22.5	23.7	23.3	25.9
9/16	23.5	23.9	21.5	22.3	22.4	25.1
5/8	22.8	22.7	22.0	20.2	22.0	25.4
11/16	21.7	19.2	20.3	21.4	20.8	25.6
3/4	21.0	21.0	20.3	20.8	21.2	22.1
13/16	19.9	17.7	19.3	20.0	19.7	20.7
7/8	21.4	22.3	19.5	21.6	19.6	20.3
15/16	20.3	19.7	19.3	20.8	19.0	19.5
1	19.6	19.9	18.0	19.1	18.3	19.3
1 1/8	18.6	18.4	17.7	18.2	18.1	19.8
1 1/4	18.3	25.7	16.0	17.6	18.3	19.8
1 3/8	18.1	17.6	17.4	17.3	17.6	19.3
1 1/2	17.5	14.9	15.9	17.3	17.4	17.4
1 5/8	15.4	16.8	15.3	17.7	17.1	19.9
1 3/4	16.4	16.6	15.1	14.6	16.8	18.7
1 7/8	16.4	16.1	14.3	16.1	16.6	17.6
2	16.0	12.5	13.8	14.8	15.9	17.0
2 1/4	13.8	14.1	12.8	13.7	15.9	15.9
2 1/2	12.6	12.3	13.2	14.1	15.6	15.7
2 3/4	11.4	12.5	10.9	13.1	15.7	15.5

Table 2-b Experimental Jominy Hardness Profile data for AISI/SAE 4130 Steel

Interval	Specimen #4		Specimen #5		Specimen #6	
(inch)	Side 1	Side 2	Side 1	Side 2	Side 1	Side 2
1/16	48.9	49.0	N/A		48.4	46.5
1/8	48.6	48.1			48.3	47.3
3/16	47.9	47.0			46.7	45.9
1/4	46.7	46.9			43.6	41.1
5/16	40.6	42.4			36.2	36.4
3/8	37.3	36.9			33.4	33.8
7/16	34.7	35.3			32.2	31.4
1/2	33.2	30.9			29.2	29.6
9/16	32.0	27.7			28.5	28.5
5/8	30.6	29.4			27.3	27.5
11/16	28.3	27.4			26.1	27.0
3/4	27.3	27.8			26.5	26.0
13/16	27.9	26.7			26.1	25.7
7/8	26.3	26.0			25.4	25.7
15/16	26.4	26.2			25.5	25.3
1	23.5	25.7			23.1	25.1
1 1/8	23.2	23.8			23.8	24.4
1 1/4	24.1	24.3			23.0	24.8
1 3/8	23.8	23.7			22.7	23.0
1 1/2	23.5	23.0			22.1	23.2
1 5/8	23.1	22.2			21.8	22.2
1 3/4	22.3	21.9			21.3	21.0
1 7/8	21.3	22.3			20.8	21.4
2	22.1	22.6			20.7	19.9
2 1/4	21.1	20.5			19.9	19.1
2 1/2	19.1	20.3			19.1	19.5
2 3/4	18.1	20.0			18.0	17.0

Table 2-c. Experimental Jominy Hardness Profile data for AISI/SAE 4140 Steel

Interval	Specimen #7		Specimen #8		Specimen #9	
(inch)	Side 1	Side 2	Side 1	Side 2	Side 1	Side 2
1/16	57.7	55.8	56.2	55.4	56.4	57.4
1/8	55.9	56.5	55.2	55.0	55.6	55.2
3/16	56.3	55.0	54.6	54.5	55.3	54.6
1/4	55.3	54.7	53.8	53.0	54.1	55.0
5/16	55.2	54.6	53.3	53.2	54.4	54.1
3/8	55.3	54.5	53.0	53.3	54.7	54.6
7/16	54.6	54.3	52.8	52.5	54.4	54.6
1/2	55.0	54.1	50.8	52.6	54.5	53.9
9/16	55.1	54.0	50.6	50.3	54.3	54.9
5/8	54.4	53.9	49.5	49.9	53.7	53.7
11/16	53.7	53.9	48.3	47.4	53.0	52.7
3/4	53.1	52.2	47.4	45.9	52.2	52.3
13/16	52.2	51.8	44.8	45.1	52.5	51.4
7/8	52.3	51.5	43.2	43.4	51.1	50.6
15/16	51.0	49.8	41.7	41.8	50.3	49.8
1	51.6	49.0	40.8	40.1	49.4	48.0
1 1/8	47.5	46.4	38.4	38.0	46.6	46.5
1 1/4	46.6	45.5	36.9	35.6	44.6	45.1
1 3/8	46.2	43.7	34.9	35.0	42.4	43.3
1 1/2	43.8	41.8	34.0	33.3	41.6	41.6
1 5/8	44.4	41.7	33.3	33.9	39.3	41.1
1 3/4	40.7	40.8	33.1	31.9	39.5	38.7
1 7/8	40.3	38.9	32.2	31.8	38.2	38.9
2	40.0	38.9	31.3	30.7	37.1	37.6
2 1/4	37.8	36.6	31.1	30.2	35.9	36.4
2 1/2	37.7	34.3	30.2	29.5	35.0	35.1
2 3/4	36.1	34.1	30.0	29.4	34.5	34.2

Table 2-d. Experimental Jominy Hardness Profile data for AISI/SAE 4340 Steel

Interval	Specimen #10		Specimen #11		Specimen #12	
(inch)	Side 1	Side 2	Side 1	Side 2	Side 1	Side 2
1/16	57.3	52.5	56.0	56.3	52.2	47.6
1/8	57.3	55.2	56.3	55.9	52.2	48.5
3/16	55.8	54.0	55.7	55.5	51.4	50.0
1/4	55.2	54.2	55.3	54.7	50.4	50.0
5/16	53.6	53.9	55.5	55.1	51.5	49.7
3/8	53.9	52.6	54.6	55.2	52.2	48.5
7/16	54.4	53.5	54.8	54.3	51.9	49.6
1/2	55.4	53.1	54.9	54.7	52.1	49.9
9/16	53.7	53.8	54.3	55.0	49.7	48.9
5/8	53.6	52.9	54.6	54.4	51.4	48.1
11/16	53.3	53.5	53.8	54.2	51.7	47.9
3/4	55.0	53.7	53.7	53.6	50.0	46.6
13/16	54.9	53.3	53.7	53.6	50.5	47.0
7/8	54.8	53.2	53.8	54.0	49.1	48.5
15/16	54.0	53.2	53.5	54.0	50.1	49.3
1	54.4	53.4	53.9	54.1	49.9	50.1
1 1/8	53.2	53.8	52.7	54.1	48.7	49.1
1 1/4	54.8	53.0	53.4	53.3	48.5	48.7
1 3/8	51.9	53.5	52.8	54.0	48.4	48.1
1 1/2	54.4	52.6	54.1	53.2	48.4	48.4
1 5/8	53.1	52.4	53.1	53.5	48.7	47.4
1 3/4	54.7	53.5	53.3	53.8	49.0	47.1
1 7/8	54.2	52.7	52.9	52.9	48.1	45.9
2	53.5	53.8	53.3	53.3	47.8	47.2
2 1/4	51.5	51.8	52.5	51.1	47.8	47.5
2 1/2	51.5	52.5	52.1	51.3	46.7	46.6
2 3/4	49.4	51.0	51.4	51.2	45.0	45.5

Table 2-e. Experimental Jominy Hardness Profile data for AISI/SAE 6150 Steel

Interval	Specimen #13		Specimen #14		Specimen #15	
(inch)	Side 1	Side 2	Side 1	Side 2	Side 1	Side 2
1/16	61.0	61.0	59.4	60.5	58.9	60.6
1/8	60.0	63.4	59.9	58.6	58.8	59.6
3/16	60.0	62.8	58.3	58.7	59.1	59.5
1/4	57.8	61.5	58.6	58.3	58.6	58.9
5/16	59.7	62.7	57.7	58.7	58.8	57.8
3/8	58.7	61.0	58.1	58.6	57.6	57.5
7/16	57.0	62.0	57.6	56.9	57.8	58.3
1/2	60.0	62.0	56.2	57.3	57.4	58.0
9/16	59.2	62.0	56.1	56.5	56.7	57.7
5/8	59.7	61.9	55.4	56.9	56.1	56.7
11/16	60.4	61.7	55.3	56.0	55.6	56.7
3/4	58.8	60.4	54.4	55.2	55.0	55.8
13/16	58.7	61.0	54.2	53.0	54.5	56.1
7/8	57.3	59.4	51.5	52.5	54.2	55.2
15/16	58.1	58.5	49.7	50.5	52.6	54.8
1	55.9	58.8	47.2	48.5	50.2	53.8
1 1/8	56.8	57.2	44.0	45.1	46.9	51.6
1 1/4	52.2	56.5	41.0	40.5	44.7	49.6
1 3/8	50.0	53.2	39.1	39.6	44.2	47.2
1 1/2	49.0	52.0	37.3	36.9	40.8	45.0
1 5/8	48.3	51.0	36.5	36.5	38.6	43.8
1 3/4	43.5	51.0	35.5	35.3	37.5	41.3
1 7/8	43.9	48.9	36.4	34.7	36.9	39.7
2	45.7	46.5	34.8	34.8	35.8	39.2
2 1/4	42.9	47.5	34.2	33.6	34.9	37.3
2 1/2	44.9	47.0	33.4	32.9	34.4	36.3
2 3/4	45.0	46.0	33.6	32.6	34.0	35.4

Table 2-f. Experimental Jominy Hardness Profile data for AISI/SAE 1045 Steel

Interval	Specimen #16		Specimen #17		Specimen #18	
(inch)	Side 1	Side 2	Side 1	Side 2	Side 1	Side 2
1/16	54.9	54.8	55.6	55.5	57.4	55.5
1/8	53.0	54.5	53.1	52.2	54.3	55.4
3/16	47.9	48.8	50.0	50.0	42.5	48.6
1/4	34.0	28.0	31.2	32.2	31.1	29.5
5/16	28.5	25.8	27.0	26.0	26.8	26.3
3/8	26.5	25.1	26.0	25.5	26.4	25.8
7/16	26.5	25.5	26.2	26.0	25.8	24.0
1/2	25.5	24.1	26.5	26.0	25.5	25.2
9/16	25.0	23.3	25.4	25.5	24.6	24.4
5/8	24.1	23.0	24.2	24.0	24.2	23.9
11/16	23.7	21.8	24.1	23.2	23.4	23.8
3/4	23.0	22.1	23.2	22.0	23.3	22.6
13/16	22.5	21.1	22.5	22.0	21.7	21.8
7/8	22.0	20.8	22.4	22.5	22.5	21.5
15/16	21.3	20.4	22.5	21.0	20.4	21.8
1	21.3	19.9	21.5	20.5	21.3	20.1
1 1/8	20.5	21.0	21.5	20.5	19.3	18.4
1 1/4	19.0	18.8	20.0	19.0	19.1	18.4
1 3/8	18.5	18.0	18.0	17.0	17.4	16.9
1 1/2	17.2	17.3	17.0	17.0	17.7	16.1
1 5/8	17.2	15.2	17.0	16.0	15.2	15.6
1 3/4	15.1	16.0	16.0	15.5	15.3	14.6
1 7/8	14.8	15.3	15.5	15.0	14.4	13.8
2	13.2	14.2	15.0	14.0	14.7	12.6
2 1/4	12.5	12.6	13.5	13.2	13.1	12.0
2 1/2	11.2	11.5	12.5	12.0	10.6	10.6
2 3/4	10.6	9.3	9.5	9.0	11.1	9.2

Table 3. ASTM Austenite Grain Sizes and Theoretical Maxim and minimum ideal critical diameter

AISI/SAE No.	8620	4130	4140	4340	6150
ASTM Grain Size	8	8	7	7	8
D_I min (in.)	1.13	1.00	1.53	2.17	1
D_I max (in.)	2.75	1.37	3.2	4.54	1.67
Base Hardenability, min	0.122	0.216	0.318	0.318	0.334
Base Hardenability, max	0.176	0.253	0.344	0.344	0.356
Sum, min	1.056	1.008	1.184	1.333	1.002
Sum, max	1.44	1.138	1.504	1.657	1.225

Table 4. Theoretical Jominy Hardness profile data

Interval (in.)	AISI/SAE 8620		AISI/SAE 4130		AISI/SAE 4140		AISI/SAE 4340		AISI/SAE 6150	
	min	max	min	max	min	max	min	max	min	max
1/16	42.2	45.4	32.2	49	55.4	57.7	47.6	57.3	58.9	61
1/4	32.7	37.2	34.4	46.9	53	55.3	50	55.3	57.8	61.5
1/2	22.5	25.9	29.2	33.2	50.8	55	49.9	55.4	56.2	62
3/4	20.3	22.1	26	27.8	47.4	53.1	46.6	50	54.4	60.4
1	18	19.9	23.1	27.1	40.1	51.6	49.9	54.4	47.2	58.8
1 1/4	16	25.7	23	24.8	35.6	46.6	48.5	54.8	40.5	56.5
1 1/2	14.9	17.5	22.1	23.9	33.3	41.8	48.4	54.4	37.3	52
1 3/4	14.6	18.7	21	23	31.9	40.8	47.1	54.7	35.3	51
2	12.5	17	19.7	22.6	30.7	40	47.2	53.8	34.8	46.5

Table 5. J, D_I, H and Do values for AISI/SAE 1045 Steel

J (in.)	D_I (in.)	Hmin	Hmax	Do,min (in.)	Do,max (in.)
0.19	1.40	0.25	0.3	0.3	0.32

Table 6. Average Martensite Hardness of Jominy Bars

Jominy Spec No.	AISI/SAE No.	Avg. Wt. Pct. Carbon	Hardness (Rc)
1-3	8620	0.205	31
4-6	4130	0.305	38
7-9	4140	0.405	45.56
10-12	4340	0.405	51.41
13-15	6150*	0.505	48
16-18	1045	0.465	35

(a) **(b)** **(c)**

Figure 2-a Schematic diagrams of the microstructures in the AISI/SAE 8620 Jominy Bar. (a) ___inches from the quenched end, (b) ____inches from the quenched end, (c) ___inches from the quenched bar.

(a) **(b)** **(c)**

Figure 2-b Schematic diagrams of the microstructures in the AISI/SAE 4130 Jominy Bar. (a) ___inches from the quenched end, (b) ____inches from the quenched end, (c) ___inches from the quenched bar

(a) **(b)** **(c)**

Figure 2-c Schematic diagrams of the microstructures in the AISI/SAE 6150 Jominy Bar. (a) ___inches from the quenched end, (b) ____inches from the quenched end, (c) ___inches from the quenched bar

(a) (b) (c)

Figure 2-d Schematic diagrams of the microstructures in the AISI/SAE 4340 Jominy Bar. (a) ___inches from the quenched end, (b) ____inches from the quenched end, (c) ___inches from the quenched bar

(a) (b) (c)

Figure 2-e Schematic diagrams of the microstructures in the AISI/SAE 4140 Jominy Bar. (a) ___inches from the quenched end, (b) ____inches from the quenched end, (c) ___inches from the quenched bar

(a) (b) (c)

Figure 2-f Schematic diagrams of the microstructures in the AISI/SAE 1045 steel Jominy Bar. (a) ___inches from the quenched end, (b) ____inches from the quenched end, (c) ___inches from the quenched bar

IV. CALCULATION

1. Maximum and minimum ideal critical diameter of alloy steels.

For example, AISI/SAE steel 8620

$D_{I,min}$

$D_{I,min}$: ASTM grain size - #8, C-0.18 wt%, Mn-0.7 wt%, Si-0.15 wt%, Cr-0.40 wt%, Mo-0.15 wt%, Ni-0.40 wt% from Table 1 of this report.

Because of the weight percent of carbon is 0.18, according to the table M.1 in the lab manual of pg 123, Base hardenability = 0.122.

Hardenability characteristics of alloy elements are Mn-0.523, Si-0.043, Cr-0.270, Mo-0.161, Ni-0.059. Therefore, the sum of characteristics = 1.056.

$D_{I,min}$ = 1.13 inch

$D_{I,max}$

$D_{I,max}$: ASTM grain size - #8, C-0.23 wt%, Mn-0.9 wt%, Si-0.35 wt%, Cr-0.70 wt%, Mo-0.25 wt%, Ni-0.70 wt% from Table 1 of this report.

Because of the weight percent of carbon is 0.23, according to the table M.1 in the lab manual of pg 123, Base hardenability = 0.176.

Hardenability characteristics of alloy elements are Mn-0.602, Si-0.095, Cr-0.400, Mo-0.244, Ni-0.099. Therefore, the sum of characteristics = 1.440.

$D_{I,max}$ = 2.75inch

2. Critical diameter of AISI/SAE 1045 steels for a water quench with no circulations

According to figure 1-f in this report, J = 0.205 inches
According to Figure 8.1 in the lab manual, D_I = 1.43 inches
According to table 8.6 in the lab manual, H = 0.25 – 0.30
According to figure 8.2 in lab manual, Do min is 0.28 inches and Do max is 0.30 inches

V. DISCUSSION

1. The experimental data shows that increasing the amounts of alloy elements increases the hardenability. Explain why this is the case.

Substitution alloy elements like Cr, Mo, Mn, and Ni make the proeutectoid ferrite, pearlite and bainite reactions go slow. This explains that in the ferrite start the pearlite start and finish and the bainite start and finish curves on the isothermal and continuous cooling diagram being shifted to the right of x-axis (time). In this process, martensite is formed at slower cooling rates and at greater distances along the Jominy bar from the quenched end being transformed to martensite. In general, the greater the total substitution alloy element content, the slower the diffusionally controlled proeutectoid ferrite, pearlite and bainite reactions, and the greater the hardenability (Smith).

2. Describe what the difference between hardness and hardenability is.

Hardness is one of mechanical properties of a material that describes its resistance to penetration by a hard object under a load (Metal handbook). Hardenability is a property of steel that describes ability to transform to martensite on quenching from austenitite condition.

3. Which steel is harder in the martensitic condition? AISI/SAE 6150 or AISI/SAE 4340? Why?

AISI/SAE 6150 is harder in martensitic condition because it has higher carbon content than AISI/SAE 4340. Martensite hardness depends on the carbon content of steel.

4. Which steel is more hardenable (has higher hardenability)? AISI/SAE 6150 or AISI/SAE 4340? Why?

AISI/SAE 4340 is more hardenable than the AISI/SAE 6150. Because the AISI/SAE 4340 contains a greater amount of substitutional alloy elements than the AISI/SAE 6150.

5. It is desired to make a two inch diameter through hardened steel part having an as quenched hardness of about Rc 62 by oil quenching with moderate circulation. What steel from Table 19 on p. 152 of Ref.[4] would you select? Back up your selection with calculation

First, the steel should have enough carbon to give a hardness of Rc 62. Second, steels should contain enough alloy element to give an actual critical diameter Do of 2.00 inches.

According to the Table M2 in the lab manual, the minimum carbon content must be 0.53 wt %. According to Table 19 on page 152 of the ASM handbook, 10^{th} Ed, Vol. 1 the following AISI/SAE alloy steels (4161, 5060, 5160, 8660, and 9260) satisfy these requirements.

To guarantee a critical diameter Do of 2.00 select the steel with minimum Do value of at least 2.00 inches from the above three steels. It is important to determine the D_I corresponding to a Do of 2.00 inches for an oil quench with moderate circulation for the first. Then calculate the minimum of D_I values for the above listed steels using their minimum carbon and alloy element content values and an ASTM grain size of 8 to see which of them has a minimum D_I value greater than the required D_I.

According to the Table 8.6 on page 68 of the lab manual minimum value of H is 0.35 (oil quenching and moderate circulation). According to figure 8.2 on page 69 of the lab manual D_I has the minimum value of 3.7 inch for H is 0.35 and Do is 2.00 inches.

According to the Table 19 of ASM handbook, three steels have the minimum carbon and alloy element contents are following:

Minimum carbon and alloy element content of alloy steels

AISI/SAE No.	Minimum Alloy Element Content (wt%)					
	C	Mn	Si	Ni	Cr	Mo
4161	0.54	0.75	0.15	-	0.70	0.25
5060	0.56	0.75	0.15	-	0.40	-
5160	0.56	0.75	0.15	-	0.70	-
8660	0.56	0.75	0.15	0.40	0.40	0.15
9260	0.56	0.75	1.80	-	-	-

According to the Table M1 on page 123 of the lab, the minimum base hardenabilities for an ASTM grain size of 8. The minimum alloy characteristic values and the minimum value of D_I values are following:

Minimum D_I, min Values

AISI/SAE No.	Minimum Alloy Element Content (wt%)							D_I min(in)
	C	Mn	Si	Ni	Cr	Mo	Total	
4161	0.360	0.544	0.043	-	0.400	0.244	1.591	3.90
5060	0.367	0.544	0.043	-	0.270	-	1.224	1.67
5160	0.367	0.544	0.043	-	0.400	-	1.354	2.26
8660	0.367	0.544	0.043	0.059	0.270	0.161	1.444	2.78
9260	0.367	0.544	0.354	-	-	-	1.265	1.84

AISI/SAE 4161 has a D_I min greater than 3.70, it is the only steel in table 19 of the ASM handbook which is guaranteed to through harden for a 2.00 inches diameter part.

Reference

[1] ***Metals Handbook***, 9th Ed., 9, ***Metallography and microstructures***, Amer. Soc. Metals, Metals Park, Ohio.

[2] ***Laboratory manual, Materials selection in mechanical design***, Marquette University, Raymond Fournelle. Fall 2005.

[3] **Alloying Elements and Their Effects and Hardenability**, 1961, Republic Steel Corporation, Cleveland, Ohio.

[4] ***ASAM Handbook***, 10th Ed., Vol. 1, ***Properties and Selection: Irons, Steels, and Highperformance Alloys***, 1990, ASM International, Materials Park, Ohio.