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C. L. Packard
C. M. Edstrom

Rockwell International

Energy Systems Group
Rocky Flats Plant
P.O. Box 464
Golden, Colorado 80401

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Microstructure
Mechanical Properties
Forging
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C. L. Packard and C. M. Edstrom

Abstract. The objective of this project was to evaluate and characterize the effects of various forging parameters on the metallographic structure and mechanical properties of 304L stainless steel forgings. Upset and die forgings were produced by hammer and Dynapak forging with forging temperatures ranging from 760-1145 °C, upset reductions ranging from 20-60%, and annealing times ranging from 0-25 minutes at 843 °C. The carbide precipitation behavior observed was found to be a function of forging temperature and annealing time. Higher forging temperatures were beneficial in avoiding continuous carbide precipitation and annealing at 843 °C promoted increased carbide precipitation. The yield strength of the unannealed forgings decreased with increasing forging temperature and, with the exception of the 1145 °C upset forgings, was significantly lowered by annealing.

INTRODUCTION

This experiment was designed to provide a better understanding of the effect of fabrication history on the mechanical properties and microstructure of 304L stainless steel forgings. Typical microstructures obtained from various forging and heat treatment procedures are documented in this report.

A secondary aim of this experiment was to determine the forging parameters which would satisfy Sandia Laboratory Specification SS 229210 without creating a continuous carbide precipitate in the grain boundaries. This specification defines the requirements for Type 304L VAR high strength forgings. It requires a minimum tensile strength of 586 MPa (85 ksi) and a minimum yield strength of 344 MPa (50 ksi) after a partial stress-relief anneal following forging.

PROCEDURE

The evaluation was performed on both upset forgings made on the hammer and closed die forgings made on the hammer and Dynapak. In upset forging the metal flows out equally in all directions between two flat dies as the cross-sectional area of the stock increases. In closed-die forging the metal flow is restricted to the cavity within the die set.

Starting stock was 1½" diameter X 3" thick weapon reserve (WR) quality 304L slugs for the upset forgings, and 1½" diameter X 3 5/16" thick weapon reserve (WR) quality 304L slugs for the closed die forgings. The upset forgings were reduced 20-60% in 1-3 steps. The die forgings were produced using two dies. The dimensions of the die forgings are shown in Figure 1.

The forging variables for the upset forgings included forging temperature and soak time, amount of reduction per hit, number of hits, quenching practice, and anneal time. For the closed die forgings the variables included forging temperature and soak time, quenching practice, and anneal time. The forging temperatures investigated ranged from 760-1145 °C with anneal times ranging from 0-25 minutes at 843 °C. A detailed description of the forging parameters for each specimen is presented in Tables 1 and 2.

Tensile and metallographic specimens were taken from the positions diagrammed in Figure 2. The metallographic specimens of the as-received bar stock were etched in 10% oxalic acid at 3 volts for 2 minutes and examined at 1000X. All metallographic specimens of the upset and die forgings were electrolytically etched in 10% oxalic acid at 6 volts for 10-15 seconds and examined at 1000X for carbide precipitation.

RESULTS

The primary function of this report is to serve as an index of expected mechanical properties and microstructures of 304L for given forging and annealing parameters. The processing conditions for the individual upset forgings and die forgings are given in Tables 1 and 2, respectively. The testing results are presented below.

Mechanical Properties

As-Received Bar Stock

The average as-received mechanical properties of the bar stock used for the upset and die forgings were as follows:

	Tensile Strength (ksi)	Yield Strength (ksi)	Percent Elongation (in 0.5")
Upset Forgings	91.4	41.8	75 (average of 3 tests)
Die Forgings	93.0	42.8	77 (average of 2 tests)

Upset Forgings

The mechanical properties of the upset forgings are given in Table 3 and summarized in Figures 3 and 4. Figures 3 and 4 show the variation in longitudinal and transverse yield strengths with forging temperature for different percent reductions and anneal times. The data points are referenced as to specimen identity and amount of reduction.

Die Forgings

The mechanical properties of the die forgings produced by both the hammer and Dynapak methods are given in Table 4 and summarized in Figures 5 and 6. Figures 5 and 6 show the variation in longitudinal and transverse yield strengths with forging temperature for different anneal times. The data points are referenced as to specimen identity and forging method.

Microstructure

Photomicrographs of the as-received bar stock are included in Figure 7. Photomicrographs representative of the upset forgings and die forgings are included in Figures 8 and 9. The type of precipitate present in the forgings is described in Tables 3 and 4 and summarized by forging temperature in Tables 5 and 6.

OBSERVATIONS

1. At a forging temperature of 760 °C, the upset forgings had a continuous precipitate in the grain boundaries of the unannealed specimens and within the grains of the annealed specimens in the prior austenitic grain boundaries. Before and after annealing the specimens die forged at 760 °C had a dispersed precipitate.

2. The blanks upset forged at 860 °C with 20 and 40% reduction also exhibited continuous precipitate in the grain boundaries of the unannealed specimens and in the prior austenitic grain boundaries of the annealed specimens. However, the specimens upset forged with 60% reduction were almost free of precipitate in the unannealed condition and had a dispersed precipitate after annealing. The unannealed and annealed die forgings produced at this temperature had either a dispersed precipitate or a continuous precipitate outside of the grain boundaries.

3. The 20% reduction upsets forged at 900 °C had a light grain boundary precipitate before annealing, a heavier continuous grain boundary precipitate after a 7½ minute anneal, and a continuous precipitate outside of the grain boundaries after a 25 minute anneal. The single hit 40% reduction upsets exhibited either a light dispersed or continuous grain boundary precipitate before annealing and a continuous grain boundary precipitate after annealing. The double hit 40% reduction upsets exhibited dispersed and continuous precipitates (both in and outside of the grain boundaries) before annealing, and a continuous precipitate outside of the grain boundaries after annealing.

4. At a forging temperature of 950 °C, both the upset and die forgings had either no precipitate or a light dispersed precipitate in the unannealed

condition. Annealing brought out a continuous grain boundary precipitate in the 20 and 40% reduction upset forgings and a dispersed precipitate in the die forgings.

5. At a forging temperature of 1145 °C, a continuous grain boundary precipitate was present after annealing in the forgings upset with 20, 40, and 60% reductions. In the unannealed condition a dispersed precipitate was present in the air-quenched 20, 40, and 60% reduction specimens; very little precipitate was present in the corresponding water-quenched specimens.

6. Annealing at 843 °C promoted increased carbide precipitation in both the upset and die forgings.

7. For a given forging temperature and anneal time, increased soak time before forging generally had little effect on the type of precipitate formed.

8. No continuous grain boundary precipitate was present in the die forgings at any of the forging temperatures investigated.

9. The yield strength of both the unannealed upset and die forgings decreased with increasing forging temperature.

10. The yield strength of the forgings was significantly lowered by annealing, with the exception of the specimens upset forged at 1145 °C. Annealing did not lower the mechanical properties of the 1145 °C upset forgings.

11. For the 20% reduction (900, 950 °C) upset forgings a 7½ minute anneal did not lower the yield strength to below 50 ksi. The yield strength of the 40% reduction upset forgings and the die forgings was lowered to below 50 ksi by a 7½ minute anneal.

12. For a given forging temperature, there was no consistent variation in strength or grain size between the hammer and Dynapak die forgings.

13. In most cases the type of quench did not have an effect on the strength or microstructure. (See Observation 5 for the exception).

14. The grain size was determined by percent reduction and forging temperature. The greater the reduction at low temperatures the smaller the grain size.

DISCUSSION

Austenitic stainless steels are generally heat treated by an anneal at a temperature high enough to effect carbide solution and then cooled to room temperature rapidly enough to keep the carbides in solution. Carbon exhibits a strong affinity for chromium and tends to precipitate as chromium carbide at temperatures between 490 and 870 °C. Precipitation preferentially occurs at the grain boundaries but carbides may also appear in the twin boundaries and within the grains.[1] The temperature range for which precipitation occurs is known as the sensitization range.

Precipitated carbides may be detrimental to hydrogen compatibility, strength, and corrosion resistance. Once chromium carbides have been formed, they can be removed only by annealing the steel between 1010-1120 °C followed by a sufficiently rapid cool to below 315 °C to prevent reprecipitation of carbides.[2]

A time-temperature-precipitation curve for a Type 304L steel is shown in Figure 10. This diagram defines the approximate temperature-time region in which carbide precipitation is found. The figure was constructed based on corrosion tests made in boiling acidified copper sulphate solution. The presence of intergranular attack was taken as the criterion of carbide precipitation. As shown, carbide precipitation occurs most rapidly at about 750 °C and less rapidly as the temperature is increased above or decreased below this temperature.[3]

The carbide precipitation behavior observed in this experiment was a function of forging temperature. The type of precipitate observed in the unannealed specimens at the different forging temperatures is summarized below.

1. A continuous precipitate in the grain boundaries of the single hit forgings and outside the grain boundaries of the double hit forgings was present in the 760, 860, and 900 °C forgings upset with 20 and 40% reduction.

2. Either a dispersed precipitate or a continuous precipitate outside the grain boundaries was present in the 760, 860, and 900 °C die forgings.

3. Little or no precipitate was present in the 860 °C-60% reduction, 950 °C-20% and 40% reduction, and 1145 °C-20, 40, and 60% reduction-water-quenched upset forgings.

4. Little or no precipitate was present in the 950 °C die forgings.

5. A dispersed precipitate was present in the 1145 °C air-quenched upset forgings.

These observations indicate the beneficial effect of the higher forging temperatures in avoiding continuous carbide precipitation. The time-temperature-precipitation curve shown in Figure 10 indicates that forgings produced at 760 and 860 °C may be susceptible to carbide precipitation.

All annealing in this experiment was done at 843 °C, in accordance with Sandia Laboratory Specification SS 229210 that calls for partial annealing of Type 304L VAR high strength forgings at 843 °C. Annealing at 843 °C promoted increased carbide precipitation in both the upset and die forgings. Where sensitization existed before the anneal it remained at the boundaries of the prior austenitic grains and within the recrystallized grains. Annealing brought out a dispersed or continuous grain boundary precipitate where no precipitate was present before annealing. The annealing temperature of 843 °C is within the sensitizing range.

As expected, the yield strength of both the unannealed upset and die forgings decreased with increasing forging temperature. The yield strength of the forgings was significantly lowered by annealing, with the exception of the specimens upset forged at 1145 °C. Annealing did not lower the mechanical properties of the 1145 °C upset forgings, indicating that recrystallization occurred during forging rather than during annealing. With the exception of the 20% reduction (900-950 °C) upset forgings, annealing lowered the yield strength to below 50 ksi.

The requirement to produce a 304L stainless steel forging without carbide precipitation and with a minimum 344 MPa (50 ksi) yield strength after an 843 °C (1550 °F) stress relief for one minute per 0.1" of thickness is difficult to satisfy. From the data generated in this project it appears that to satisfy the strength requirement, the forging should receive approximately 20% total reduction and be forged at 900-950 °C. A percentage reduction greater than 20% or forging at lower temperatures provides more stored energy available for recrystallization and the stainless steel is fully annealed at the 843 °C "stress relieving" temperature. However, for 20% reduction at 900-950 °C, an undesirable continuous grain boundary precipitate is present after annealing.

In general, annealing should be avoided to prevent grain boundary precipitation and loss of strength.

REFERENCES

1. H. Thielsch, "Physical Metallurgy of Austenitic Stainless Steels," *The Welding Journal*, Vol. 29, p. 589s, (1950).

2. H. Thielsch, "Alloying Elements in Chromium-Nickel Stainless Steels," *The Welding Journal*, Vol. 29, p. 365s, (1950).

3. W. O. Binder et.al., " Resistance to Sensitization of Austenitic Chromium-Nickel Steels of 0.03% Max. Carbon Content," *Transactions of the A. S. M.*, Vol. 41, p. 1322, (1949).

TABLES
(1 through 6)

TABLE 1. Processing Conditions for Upset Forgings

Forging Temp. (°C)	Soak Time (min)	No. of Hits	Total % Reduction	Type of Quench	Anneal Time at 843 °C (min)	Specimen Identity
760	2	1	20	Air	0	58
760	2	1	20	Water	0	56
760[a]	5-10	1	20	Water	0	21
760	4	1	40	Air	0	61
760	4	1	40	Water	0	59
760[a]	5-10	1	40	Water	0	23
760	2	1	20	Air	25	57
760	2	1½[b]	20	Water	25	55
760[a]	5-10	1	20	Water	25	22
760	4	1	40	Air	25	62
760	4	1	40	Water	25	60
760[a]	5-10	1	40	Water	25	24
860	5	1	20	Air	0	28
860	5	1	20	Water	0	27
860	9	1	40	Air	0	33
860	5	1	40	Water	0	31
860	5-10	2[c]	40	Hit 1-No quench, Hit 2-Water	0	19
860	5-10	2[c]	40	Hit 1-Water, Hit 2-Water	0	17
860	9	1	60[d]	Air	0	35
860	9	1	60[d]	Water	0	37
860	16	1	60[d]	Water	0	38
860	9	1	60[d]	Air	18	34
860	9	1	60[d]	Water	18	36
860	5	1	20	Air	25	29
860	5	1	20	Water	25	26
860	5	1½[b]	40	Air	25	32
860	5	1	40	Water	25	30
860	5-10	2[c]	40	Hit 1-No quench, Hit 2-Water	25	20
860	5-10	2[c]	40	Hit 1-Water, Hit 2-Water	25	18
900	5-10	1	20	Water	0	1
900	5-10	1	40	Water	0	4

a. Soaked at 900 °C for 5-10 min then cooled to 760 °C.
b. A second hit made to ensure that the upset forging was home in the stop block.
c. Two heats at soak temperature and two 20% hits.
d. Knock out procedure required lubricant and took 10-20 sec.
e. Three 20% hits.

TABLE 1. (Concluded) Processing Conditions for Upset Forgings

Forging Temp. (°C)	Soak Time (min)	No. of Hits	Total % Reduction	Type of Quench	Anneal Time at 843 °C (min)	Specimen Identity
900	30	1	40	Water	0	25
900	5-10	2[c]	40	Hit 1-No quench, Hit 2-Water	0	9
900	5-10	2[c]	40	Hit 1-Water, Hit 2-Water	0	7
900	5-10	1	20	Water	7½	2
900	5-10	1	40	Water	7½	5
900	5-10	1	20	Water	25	3
900	5-10	1	40	Water	25	6
900	5-10	2[c]	40	Hit 1-No quench, Hit 2-Water	25	10
900	5-10	2[c]	40	Hit 1-Water, Hit 2-Water	25	8
950	5-10	1	20	Water	0	11
950	5-10	1	40	Water	0	14
950	5-10	1	20	Water	7½	12
950	5-10	1	40	Water	7½	15
950	5-10	1	20	Water	25	13
950	5-10	1	40	Water	25	16
1145	1	1	20	Air	0	42
1145	1	1	20	Water	0	40
1145	1	1	40	Air	0	45
1145	1	1	40	Water	0	43
1145	1	1	60[d]	Air	0	49
1145	1	1	60[d]	Water	0	48
1145	15	3[e]	60[d]	Air	0	53
1145	15	3[e]	60[d]	Water	0	52
1145	7	1½[b]	60[d]	Air	18	50
1145	1	1	60[d]	Water	18	47
1145	21	3[e]	60[d]	Air	18	54
1145	15	3[e]	60[d]	Water	18	51
1145	1	1	20	Air	25	41
1145	1	1	20	Water	25	39
1145	1	1	40	Air	25	46
1145	1	1	40	Water	25	44

a. Soaked at 900 °C for 5-10 min then cooled to 760 °C.
b. A second hit made to ensure that the upset forging was home in the stop block.
c. Two heats at soak temperature and two 20% hits.
d. Knock out procedure required lubricant and took 10-20 sec.
e. Three 20% hits.

TABLE 2. Processing Conditions for Die Forgings

Forging Method	First Heat: Soak Temp. (°C)	First Heat: Soak Time (min)	First Heat: Quench	Second Heat: Soak Temp. (°C)	Second Heat: Soak Time (min)	Second Heat: Quench	Anneal Time at 843 °C (min)	Specimen Identity
Hammer	900	5	Water	900*	5	Water	0	C
Dynapak	900	5	Water	900*	5	Water	0	K
Hammer	900	5	Water	900*	5	Water	7½	CA
Dynapak	900	5	Water	900*	5	Water	7½	KA
Hammer	860	5	None	860	5	Water	0	E
Dynapak	860	5	None	860	5	Water	0	L
Hammer	860	5	Water	860	5	Water	0	A
Dynapak	860	5	Water	860	5	Water	0	G
Hammer	860	30	Water	860	5	Water	0	D
Dynapak	860	30	Water	860	5	Water	0	H
Dynapak	860	30	Water	860	30	Water	0	I
Hammer	860	5	None	860	5	Water	7½	EA
Dynapak	860	5	None	860	5	Water	7½	LA
Hammer	860	5	Water	860	5	Water	7½	AA
Dynapak	860	5	Water	860	5	Water	7½	GA
Hammer	860	30	Water	860	5	Water	7½	DA
Dynapak	860	30	Water	860	5	Water	7½	HA
Dynapak	860	30	Water	860	30	Water	7½	IA
Hammer	950	5	Water	950	5	Water	0	B
Dynapak	950	5	Water	950	5	Water	0	J
Hammer	950	5	Water	950	5	Water	7½	BA
Dynapak	950	5	Water	950	5	Water	7½	JA

*Soaked at 900 °C for 5 min, air cooled to 760 °C, die struck, and water quenched. Hereafter designated as 760 °C forging temperature.

TABLE 3. Mechanical Properties and Microstructure of Upset Forgings

Forging Temp. (°C)	Total % Reduction	Anneal Time at 843 °C (min)	Mechanical Properties: Tensile Strength (ksi)	Yield Strength (ksi)	% Elong. (in 0.5 in)	Type of Precipitate	Specimen Identity
760	20	0	L 96.1	67.4	64.0	C-GB	58
760			T 99.6	65.7	61.0		
760	20	0	L 95.2	66.0	66.0	C-GB	56
760			T102.6	71.5	62.0		
760	20	0	L 94.5	70.9	57.1	C-GB (light), D	21
760			L 94.5	68.9	>55.5		
760			T 97.8	65.6	>56.0		
760	40	0	L101.7	77.0	47.5	C-GB	61
760			T 97.5	61.8	62.0		
760	40	0	L103.4	77.0	48.5	C-GB	59
760			T 99.3	66.2	63.0		
760	40	0	L105.1	77.4	37.3	C-GB (light), D	23
760			L101.9	75.2	42.1		
760			T101.1	73.4	49.3		
760	20	25	L 90.3	36.6	79.0	C-NGB	57
760			T 97.4	57.9	70.0		
760	20	25	L 92.1	37.4	81.5	C-NGB	55
760			T 93.0	47.5	72.0		
760	20	25	L 92.9	39.9	>60.9	C-NGB	22
760			L 94.1	43.2	>61.5		
760			T 97.4	54.6	58.9		
760	40	25	L 93.3	39.7	74.0	C-NGB	62
760			T 92.6	47.7	68.0		
760	40	25	L 95.0	40.1	75.0	C-NGB	60
760			T 96.6	37.0	72.0		
760	40	25	L 93.7	39.9	>56.7	C-NGB, D	24
760			L 92.5	38.3	>55.4		
760			T 91.3	39.1	>56.2		
860	20	0	L 94.8	65.3	66.5	C-GB	28
860			T102.4	70.9	58.0		
860	20	0	L 95.8	66.1	68.5	C-GB	27
860			T102.6	69.0	58.0		
860	40	0	L 99.4	68.9	56.0	C-GB (light), D	33
860			T 99.4	47.1	66.0		
860	40	0	L 92.4	71.9	54.5	C-GB	31
860			T100.2	47.9	64.0		
860	40	0	L 98.2	68.5	47.1	C-NGB	19
860			L 97.8	70.5	53.8		
860			T 99.4	64.4	>55.3		
860	40	0	L 97.4	72.5	48.1	C-NGB	17
860			L 98.6	73.8	49.7		
860			T100.6	71.3	49.1		
860	60	0	L102.7	55.5	61.0	D (very light)	35
860			T 99.4	61.8	62.0		
860	60	0	L102.2	54.2	62.5	D (very light)	37
860			T 97.4	59.5	63.0		
860	60	0	L 99.5	58.7	59.0	D (very light)	38
860			T106.1	75.8	57.0		
860	60	18	L 96.9	41.8	69.0	D	34
860			T -	-	-		

D = Dispersed precipitate
C-GB = Continuous precipitate in grain boundary
C-NGB = Continuous precipitate, not in grain boundary

TABLE 3. (Continued) Mechanical Properties and Microstructure of Upset Forgings

Forging Temp. (°C)	Total % Reduction	Anneal Time at 843 °C (min)	Mechanical Properties: Tensile Strength (ksi)	Mechanical Properties: Yield Strength (ksi)	Mechanical Properties: % Elong. (in 0.5 in)	Type of Precipitate	Specimen Identity
860	60	18	L 98.0	43.0	68.0	D	36
860			T 96.0	55.0	65.0		
860	20	25	L 91.7	38.0	80.0	C-NGB	29
860			T 95.7	54.1	68.0		
860	20	25	L 91.9	37.6	80.5	C-NGB	26
860			T 93.0	35.7	78.0		
860	40	25	L 94.0	40.6	75.5	C-NGB, D	32
860			T 96.4	41.3	74.0		
860	40	25	L 94.3	40.1	75.0	C-NGB, D	30
860			T 96.7	40.6	73.0		
860	40	25	L 93.7	39.5	>54.5	C-NGB	20
860			L 91.7	37.1	>57.3		
860			T 92.9	44.4	>55.2		
860	40	25	L 95.8	40.8	>59.1	C-NGB, D	18
860			L 96.6	40.3	>59.3		
860			T 96.2	43.6	>59.3		
900	20	0	L 92.5	59.9	57.5	C-GB (light)	1
900			L 92.8	66.3	60.3		
900			T 98.5	58.8	57.7		
900	40	0	L 95.4	47.7	>55.4	D (light)	4
900			L 95.8	45.5	>55.0		
900			T101.5	67.2	>54.8		
900	40	0	L 95.4	61.1	57.3	C-GB	25
900			L 96.6	53.0	>56.5		
900			T102.3	74.6	49.5		
900	40	0	L 99.9	44.9	>61.2	C-NGB (light), D	9
900			L 97.8	68.4	57.1		
900			T103.3	67.6	51.0		
900	40	0	L100.2	55.4	55.8	C-GB, C-NGB	7
900			L 98.6	70.1	56.6		
900			T104.9	74.9	47.3		
900			T104.9	72.2	49.2		
900	20	7½	L 93.7	58.7	59.4	C-GB	2
900			L 94.1	64.8	57.7		
900			T 98.6	61.1	59.5		
900	40	7½	L 95.1	42.5	>60.1	C-GB	5
900			L 99.0	41.2	63.4		
900			T 99.4	64.4	52.5		
900	20	25	L 92.1	39.5	>59.1	C-NGB	3
900			L 92.5	36.7	>59.7		
900			T 98.2	59.5	57.2		
900	40	25	L 99.6	43.4	63.6	C-GB	6
900			L 98.5	41.9	>61.4		
900			T 97.8	42.5	>59.5		
900	40	25	L 94.4	38.4	>59.1	C-NGB, D	10
900			L 97.0	38.6	>60.2		
900			T 96.1	40.3	>59.6		
900	40	25	L 92.1	38.3	>56.4	C-NGB, D	8
900			L 91.7	36.7	>54.5		
900			T 95.4	49.7	>55.5		

D = Dispersed precipitate
C-GB = Continuous precipitate in grain boundary
C-NGB = Continuous precipitate, not in grain boundary

TABLE 3. (Concluded) Mechanical Properties and Microstructure of Upset Forgings

Forging Temp. (°C)	Total % Reduction	Anneal Time at 843 °C (min)	Mechanical Properties: Tensile Strength (ksi)	Mechanical Properties: Yield Strength (ksi)	Mechanical Properties: % Elong. (in 0.5 in)	Type of Precipitate	Specimen Identity
950	20	0	L 93.7	62.4	>58.0	None	11
950			L 92.1	48.9	>56.9		
950			T 93.3	50.1	>54.6		
950	40	0	L 95.4	39.1	>55.3	D (light)	14
950			L 95.0	41.2	>55.1		
950			T100.6	68.0	46.7		
950	20	7½	L 94.5	63.2	58.4	C-GB	12
950			L 93.7	54.6	60.5		
950			T 95.0	52.2	59.2		
950	40	7½	L 98.9	43.1	>59.4	C-GB	15
950			L 97.8	40.3	>58.9		
950			T 99.9	41.2	58.2		
950	20	25	L 93.3	48.1	-	C-GB	13
950			L 93.7	44.4	58.8		
950			T 95.4	51.3	56.0		
950	40	25	L 94.5	39.9	64.8	C-GB	16
950			L 95.0	40.3	>62.3		
950			T 93.8	36.9	61.9		
1145	20	0	L 89.3	35.1	79.5	D (heavy)	42
1145			T 88.3	34.7	82.0		
1145	20	0	L 89.3	35.0	80.5	D (light)	40
1145			T 89.3	36.6	80.0		
1145	40	0	L 89.4	32.5	79.5	C-GB (light), D	45
1145			T 83.7	37.4	82.0		
1145	40	0	L 90.4	35.8	79.0	D (very light)	43
1145			T 89.2	33.1	83.0		
1145	60	0	L 91.7	35.7	78.5	D	49
1145			T 98.5	33.6	83.0		
1145	60	0	L 90.0	35.1	75.0	D (very light)	48
1145			T 90.9	42.1	76.0		
1145	60	0	L 95.6	50.8	67.0	C-GB (light), D (light)	53
1145			T 94.9	40.3	69.0		
1145	60	0	L 95.3	44.7	69.0	D (very light)	52
1145			T 94.0	57.6	68.0		
1145	60	18	L 92.6	44.2	69.5	C-GB, D	50
1145			T 89.5	39.8	76.0		
1145	60	18	L 90.4	35.9	75.0	C-GB	47
1145			T 89.3	38.2	78.0		
1145	60	18	L 94.0	38.8	69.5	C-GB, D	54
1145			T 93.9	40.3	76.0		
1145	60	18	L 94.1	38.7	76.0	C-GB, C-NGB	51
1145			T 94.5	41.2	72.0		
1145	20	25	L 89.0	34.6	84.5	C-GB	41
1145			T 86.1	41.2	79.0		
1145	20	25	L 90.2	36.9	81.5	C-GB, D	39
1145			T 89.1	37.4	80.0		
1145	40	25	L 89.6	35.7	77.0	C-GB, D	46
1145			T 87.8	33.1	80.0		
1145	40	25	L 90.3	38.0	76.5	C-GB	44
1145			T 87.8	39.3	81.0		

D = Dispersed precipitate
C-GB = Continuous precipitate in grain boundary
C-NGB = Continuous precipitate, not in grain boundary

TABLE 4. Mechanical Properties and Microstructure of Die Forgings*

Forging Temp. (°C)	Anneal Time at 843 °C (min)	Forging Method	Mechanical Properties: Tensile Strength (ksi)	Mechanical Properties: Yield Strength (ksi)	Mechanical Properties: % Elong. (in 0.5 in)	Type of Precipitate	Specimen Identity
760*	0	Hammer	L 94.5	88.8	49.1	D	C
760			T 96.0	67.0	53.5		
760	0	Dynapak	L114.9	96.2	44.7	C-NGB (light), D	K
760			T103.1	81.1	38.8		
760	7½	Hammer	L 95.0	39.9	>53.2	D	CA
760			T 95.8	42.4	>56.4		
760	7½	Dynapak	L 95.4	39.1	>53.8	D	KA
760			T 95.4	47.3	>55.5		
860	0	Hammer	L108.4	81.9	42.0	C-NGB	E
860			T110.8	85.9	43.4		
860	0	Dynapak	L114.5	88.8	47.8	C-NGB	L
860			T100.2	71.3	47.6		
860	0	Hammer	L110.0	79.0	50.4	C-NGB	A
860			T105.9	62.4	52.0		
860	0	Dynapak	L106.8	80.7	45.6	C-NGB	G
860			T110.8	81.1	46.8		
860	0	Hammer	L106.8	80.7	46.1	C-NGB	D
860			T 97.8	65.6	53.3		
860	0	Dynapak	L107.5	81.0	44.3	D	H
860			T 99.8	70.1	48.4		
860	0	Dynapak	L110.4	83.1	49.3	C-NGB	I
860			T108.0	70.5	50.8		
860	7½	Hammer	L 95.8	43.2	>55.7	C-NGB	EA
860			T 99.0	44.4	>55.5		
860	7½	Dynapak	L 93.7	39.9	>55.7	C-NGB (light), D	LA
860			T 97.8	44.4	>55.6		
860	7½	Hammer	L 95.8	42.0	>53.5	D	AA
860			T 97.0	39.9	>56.5		
860	7½	Dynapak	L 94.5	39.9	>55.7	D	GA
860			T 97.0	43.2	>54.2		
860	7½	Hammer	L 95.0	41.6	>57.1	D	DA
860			T 95.4	41.6	>56.0		
860	7½	Dynapak	93.7	39.9	>54.0	D	HA
860			97.0	44.0	>54.2		
860	7½	Dynapak	92.9	38.3	>57.6	D	IA
860			97.0	45.2	>56.4		
950	0	Hammer	108.4	83.5	52.7	None	B
950			106.8	81.1	48.8		
950	0	Dynapak	104.7	74.2	53.1	D (light)	J
950			100.2	53.0	>56.8		
950	7½	Hammer	86.0	41.6	>56.1	D	BA
950			95.4	56.2	>54.7		
950	7½	Dynapak	96.8	41.4	>54.6	D	JA
950			95.4	48.5	>55.8		

D = Dispersed precipitate
C-GB = Continuous precipitate in grain boundary
C-NGB = Continuous precipitate, not in grain boundary

*See Table 2 for processing details.

TABLE 5. Summary of Type of Precipitate Present in Upset Forgings at Given Forging Temperatures

Anneal Time (min)	Reduction	Forging Temperature (°C) at Which Given Type of Precipitate is Present*: No Precipitate	Dispersed Precipitate	Continuous Precipitate: Not In Grain Boundary	Continuous Precipitate: In Grain Boundary
0	One 20% hit	950	760, 1145		760, 860, (900)
0	One 40% hit		760, 860, 900, (950), (1145)		760, 860, 900, (1145)
0	Two 20% hits		900	860, 900	900
0	One 60% hit		(860), 1145		
0	Three 20% hits		(1145)		(1145)
7½	One 20% hit				900, 950
7½	One 40% hit				900, 950
18	One 60% hit		860, 1145		1145
18	Three 20% hits		1145	1145	1145
25	One 20% hit		1145	760, 860, 900	950, 1145
25	One 40% hit		760, 860, 1145	760, 860	900, 950, 1145
25	Two 20% hits		860, 900	860, 900	

*Parentheses denote light precipitate.

TABLE 6. Summary of Type of Precipitate Present in Die Forgings at Given Forgings at Given Forging Temperatures

Anneal Time (min)	Forging Method	Forging Temperature (°C) at Which Given Type of Precipitate is Present*: No Precipitate	Dispersed Precipitate	Continuous Precipitate: Not In Grain Boundary	Continuous Precipitate: In Grain Boundary
0	Hammer	950	760	860	
0	Dynapak		760, 860, (950)	(760), 860	
7½	Hammer		760, 860, 950	860	
7½	Dynapak		760, 860, 950	(860)	

*Parentheses denote light precipitate.

ILLUSTRATIONS
(Figures 1 through 10)

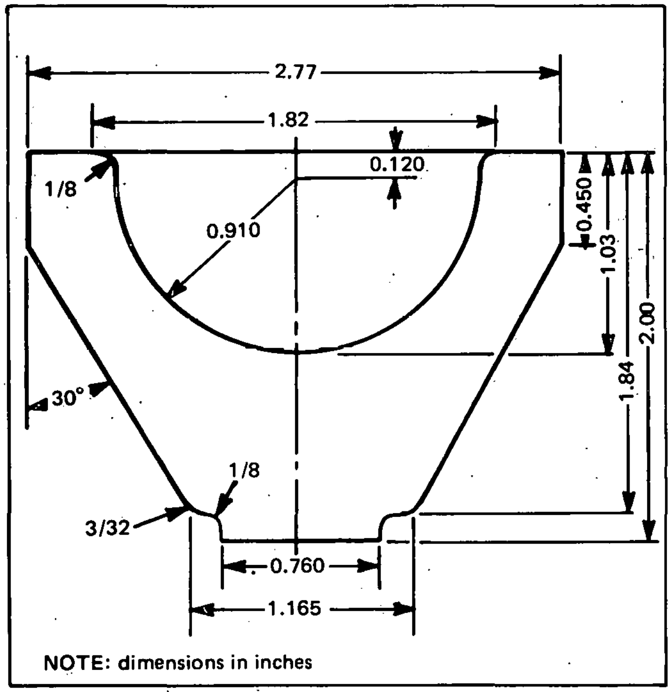


FIGURE 1. Die Forging

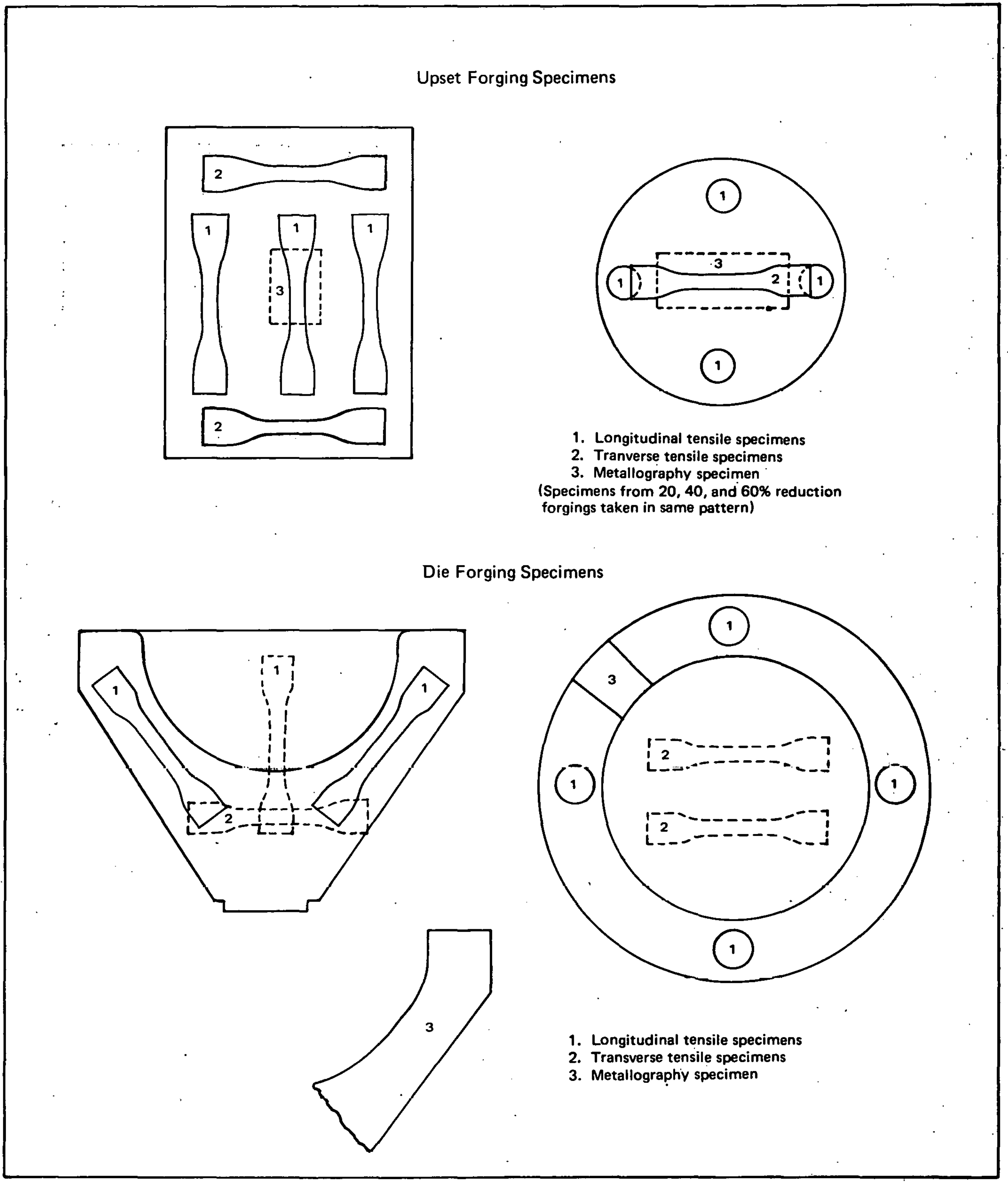
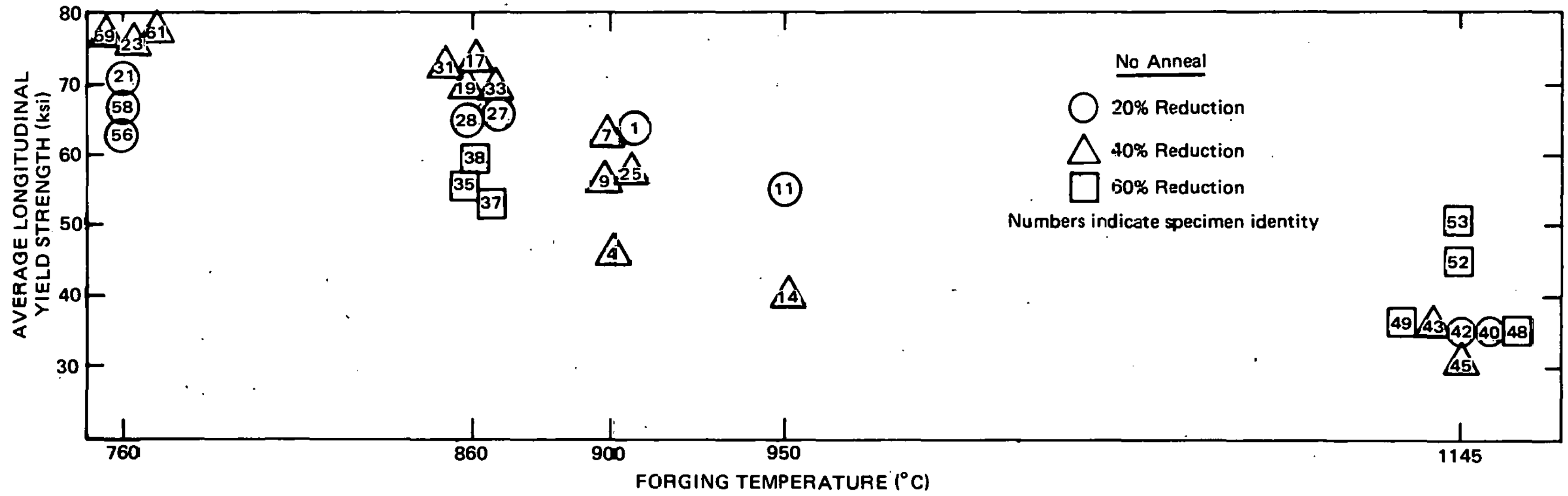
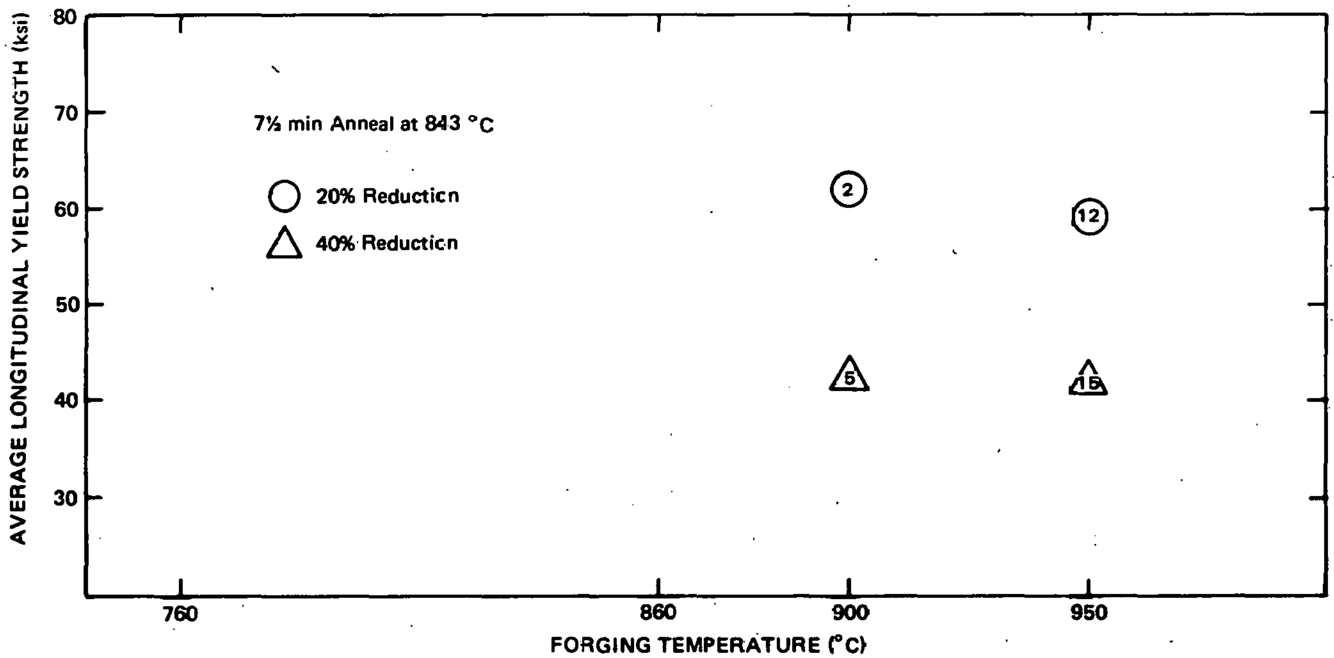


FIGURE 2. Positions of Tensile and Metallographic Specimens

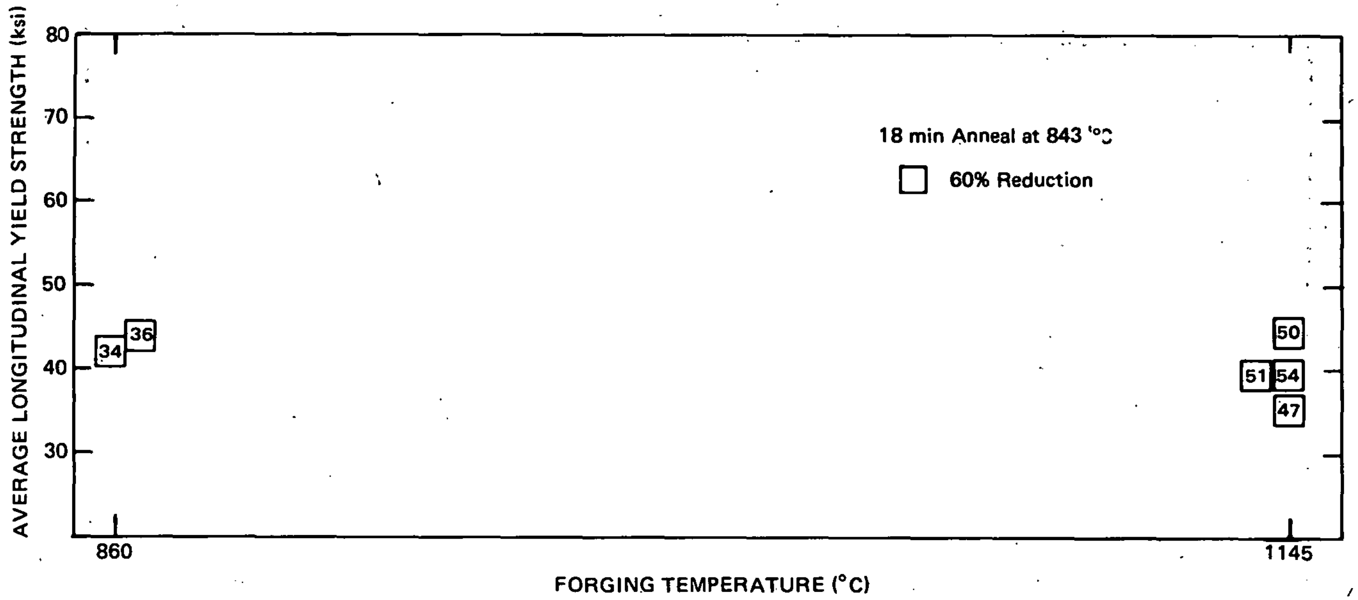
FIGURES 3-1, -2, -3, and -4. Variation in Longitudinal Yield Strength of Upset Forgings With Forging Temperature



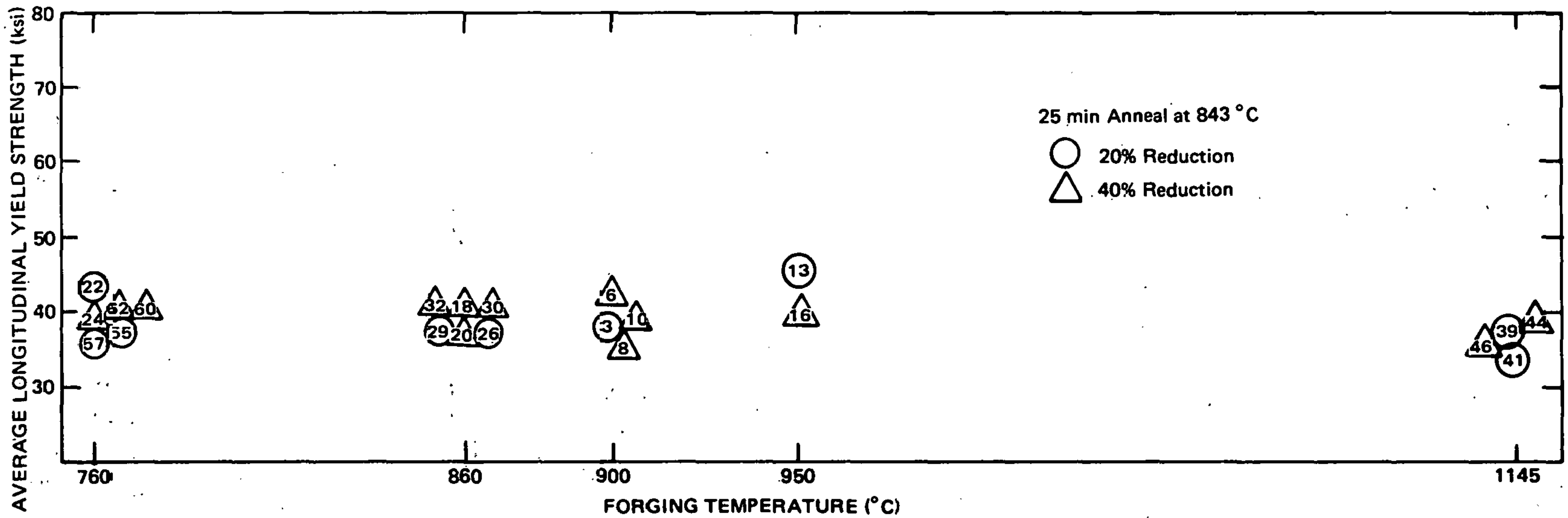
3-1



3-2

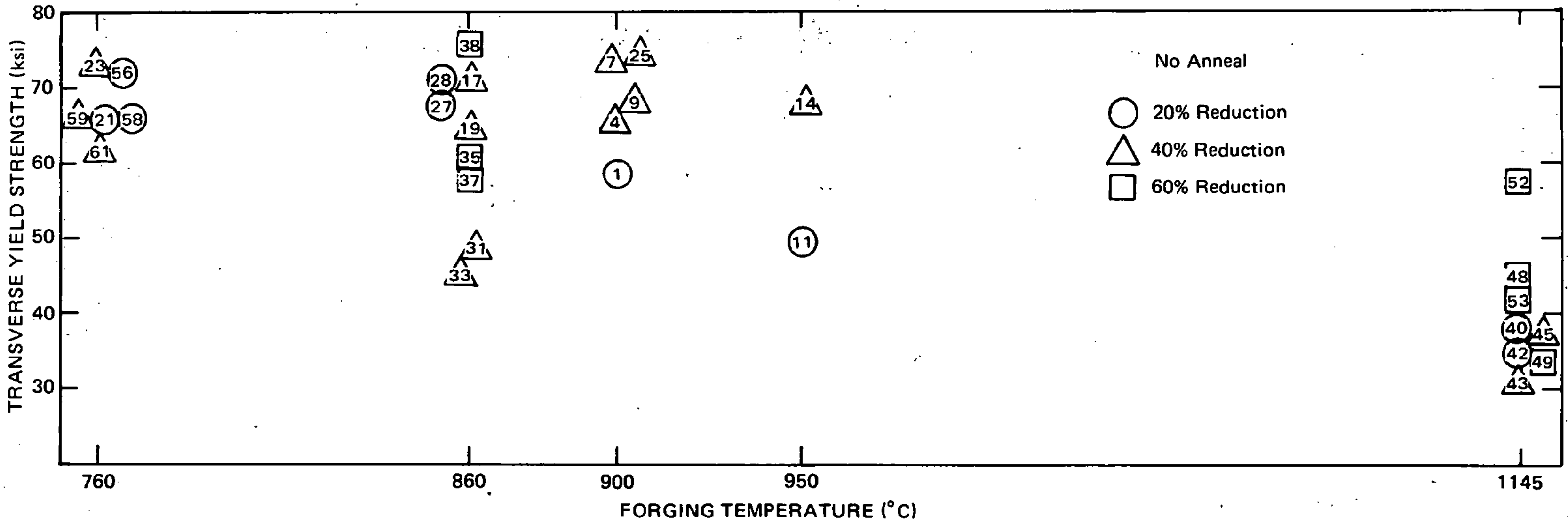

AVERAGE LONGITUDINAL YIELD STRENGTH (ksi)
80
70
60
50
40
30
18 min Anneal at 843 °C
60% Reduction
34
36
50
51
54
47
860
1145
FORGING TEMPERATURE (°C)

3-3

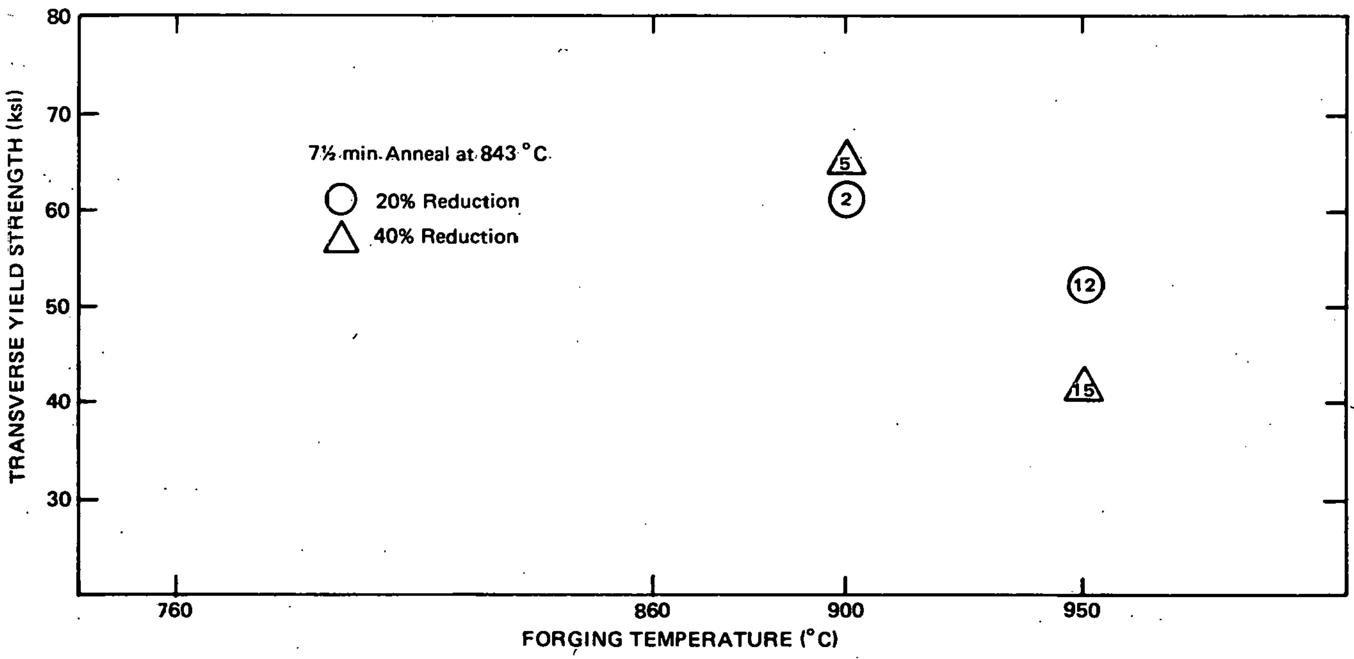

AVERAGE LONGITUDINAL YIELD STRENGTH (ksi)
80
70
60
50
40
30
25 min Anneal at 843 °C
20% Reduction
40% Reduction
22
24
62
60
57
55
32
18
30
29
20
26
6
3
10
8
13
16
46
39
44
41
760
860
900
950
1145
FORGING TEMPERATURE (°C)

3-4

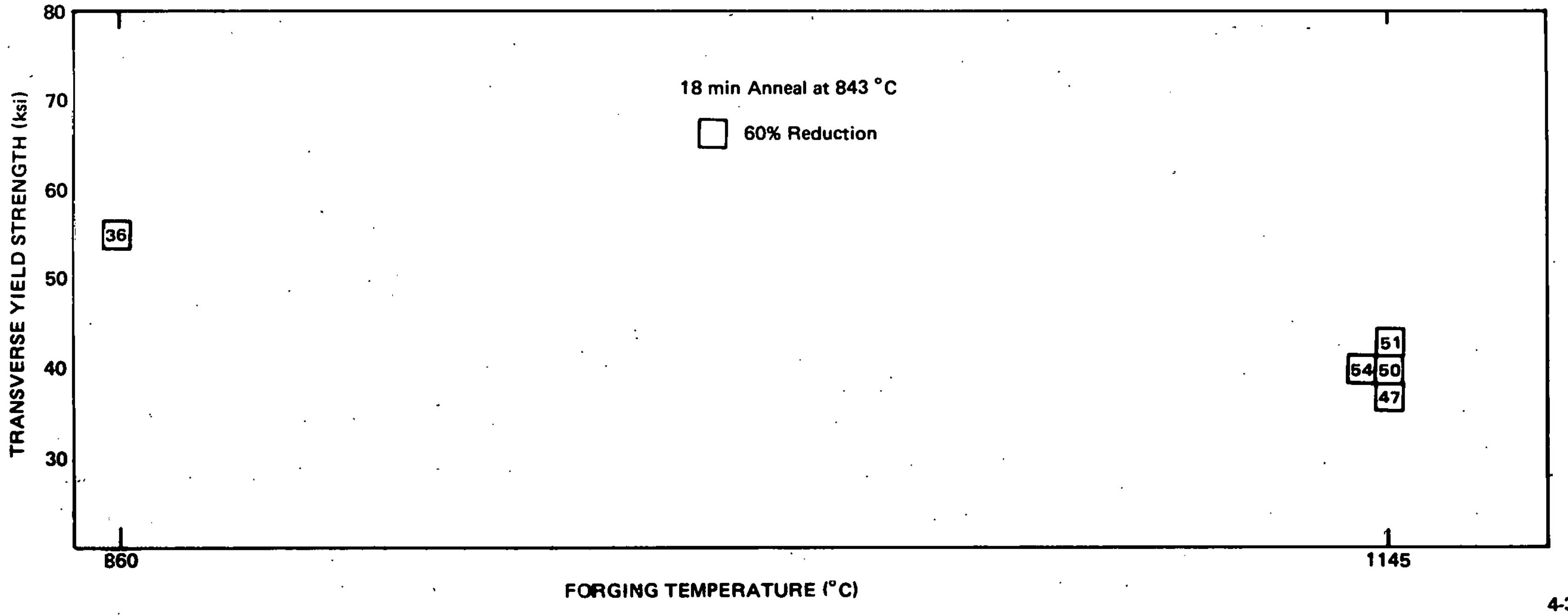
FIGURES 4-1, -2, -3, and -4. Variation in Transverse Yield Strength of Upset Forgings With Forging Temperature



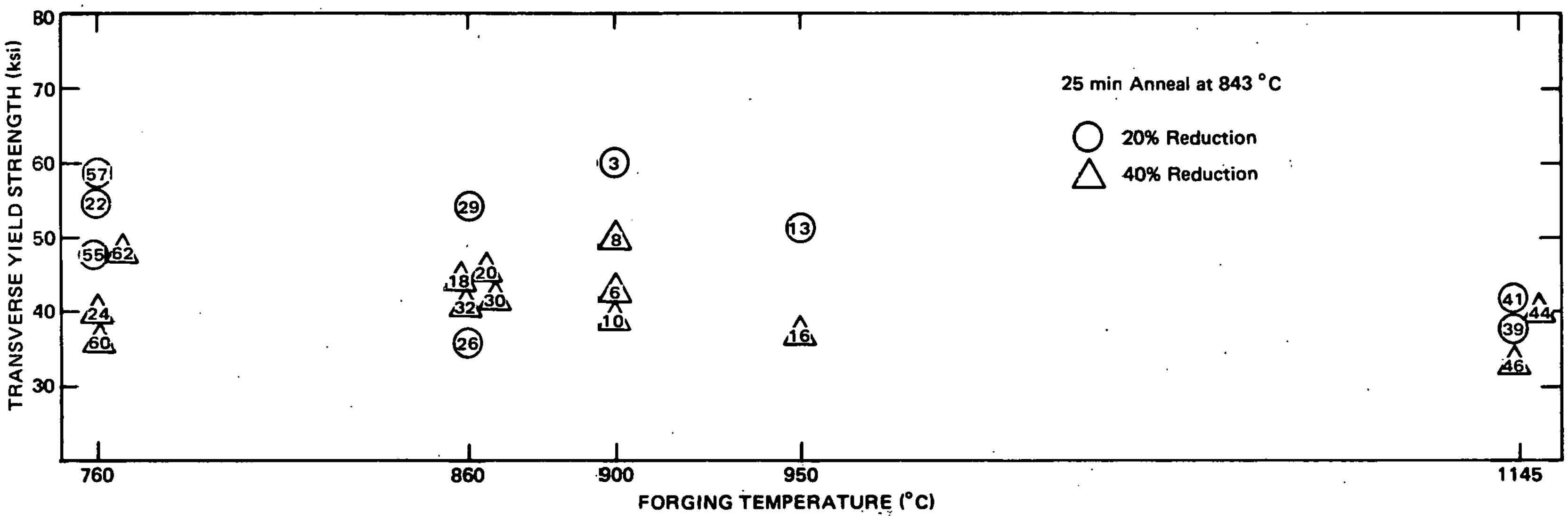
4-1



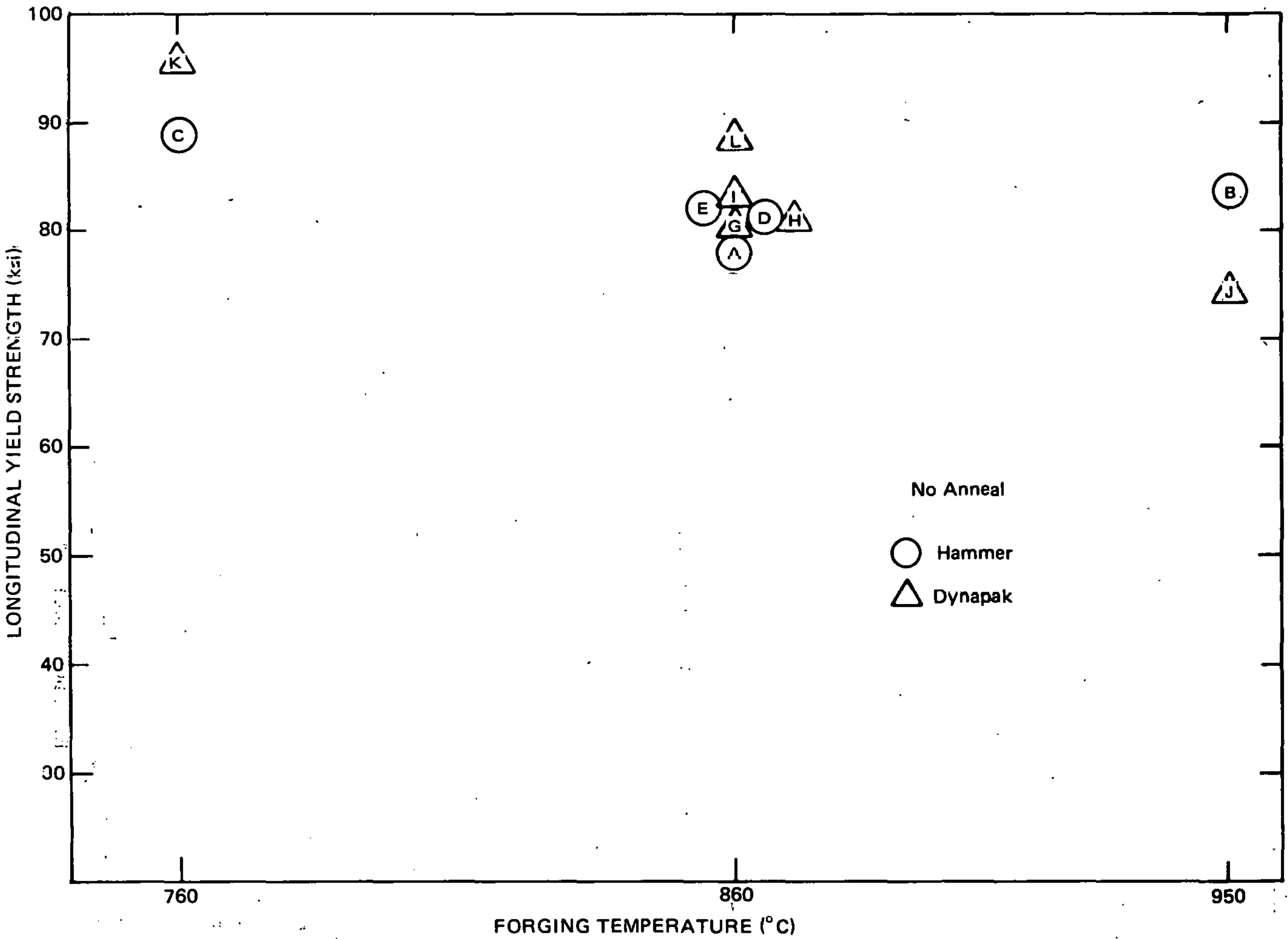
4-2


18 min Anneal at 843 °C
60% Reduction
TRANSVERSE YIELD STRENGTH (ksi)
80
70
60
50
40
30
36
51
54
50
47
860
1145
FORGING TEMPERATURE (°C)

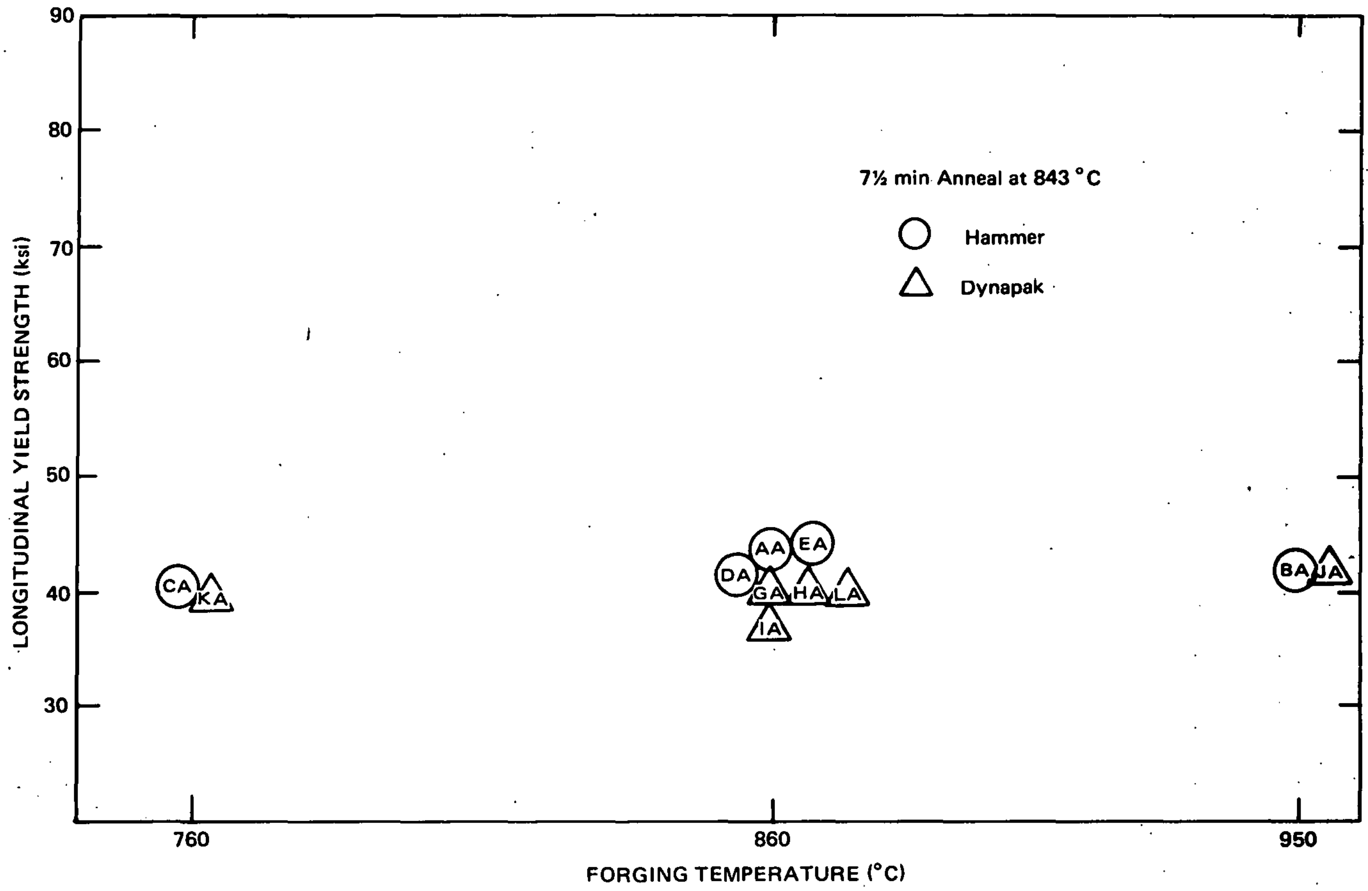
4-3


25 min Anneal at 843 °C
20% Reduction
40% Reduction
TRANSVERSE YIELD STRENGTH (ksi)
80
70
60
50
40
30
57
22
55
62
24
60
29
18
20
32
30
26
3
8
6
10
13
16
41
44
39
46
760
860
900
950
1145
FORGING TEMPERATURE (°C)

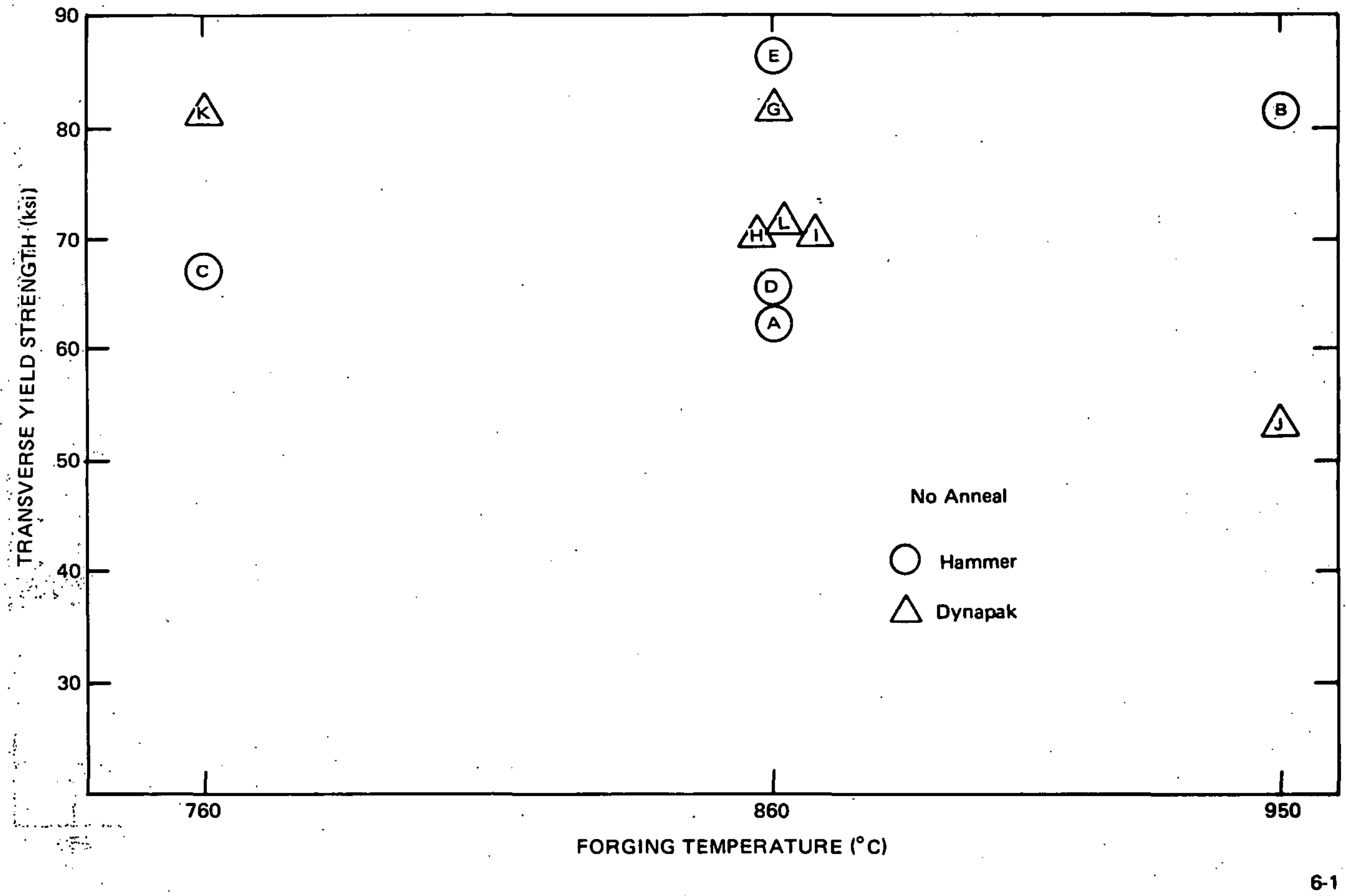
4-4



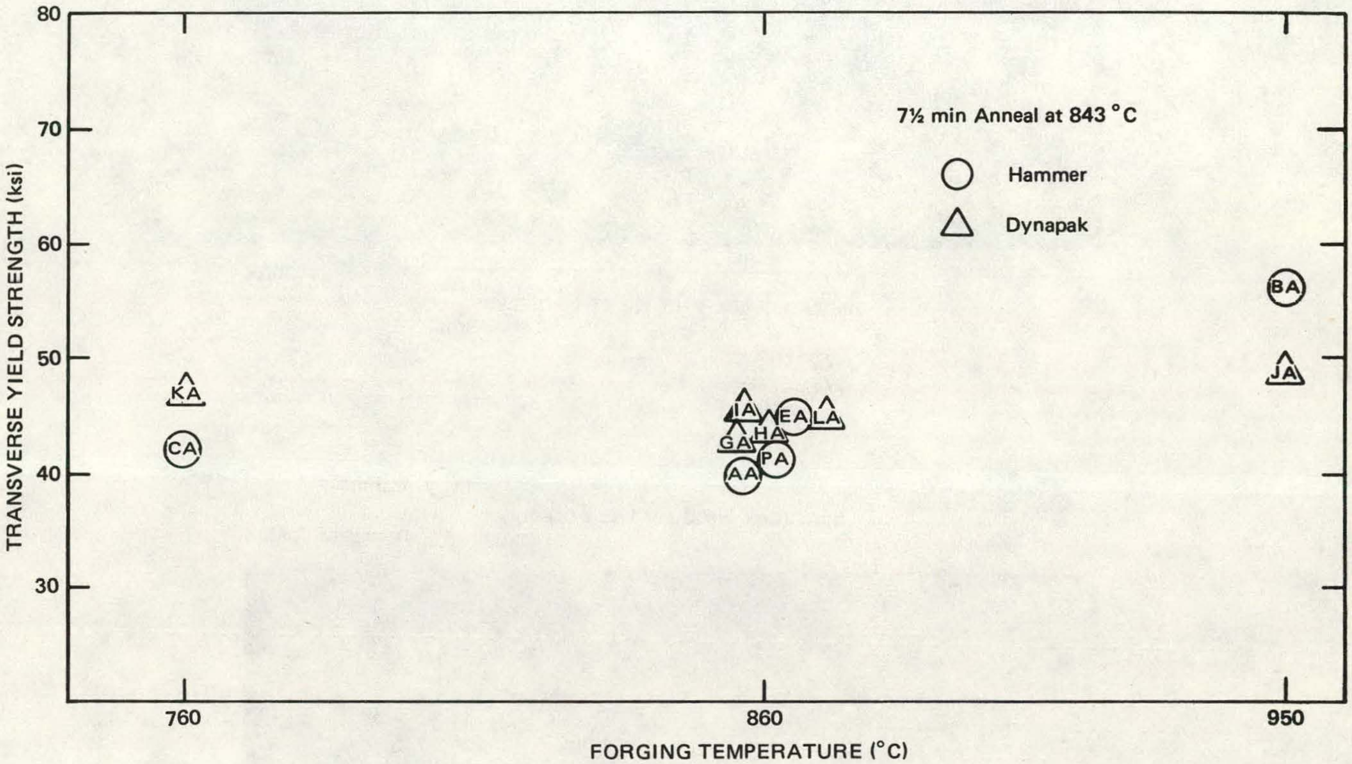
FIGURES 5-1 and -2. Variation in Longitudinal Yield Strength of Die Forgings With Forging Temperature


7½ min Anneal at 843 °C
Hammer
Dynapak
LONGITUDINAL YIELD STRENGTH (ksi)
90
80
70
60
50
40
30
CA
KA
DA
AA
EA
GA
HA
LA
IA
BA
JA
760
860
950
FORGING TEMPERATURE (°C)

5-2

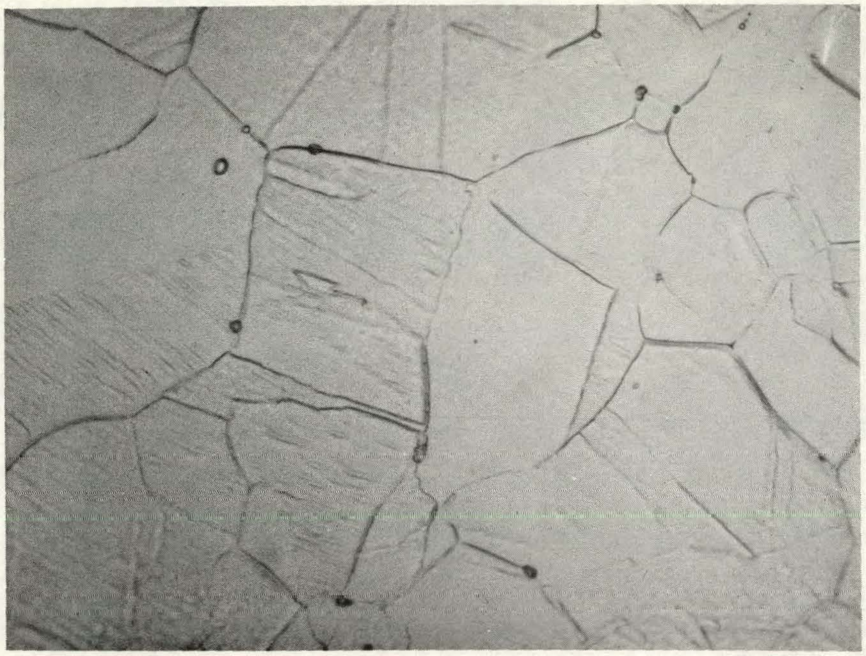


FIGURES 6-1 and -2. Variation in Transverse Yield Strength of Die Forgings With Forging Temperature



7½ min Anneal at 843 °C
Hammer
Dynapak
TRANSVERSE YIELD STRENGTH (ksi)
80
70
60
50
40
30
FORGING TEMPERATURE (°C)
760
860
950
KA
CA
IA
EA
LA
GA
HA
PA
AA
BA
JA

6-2



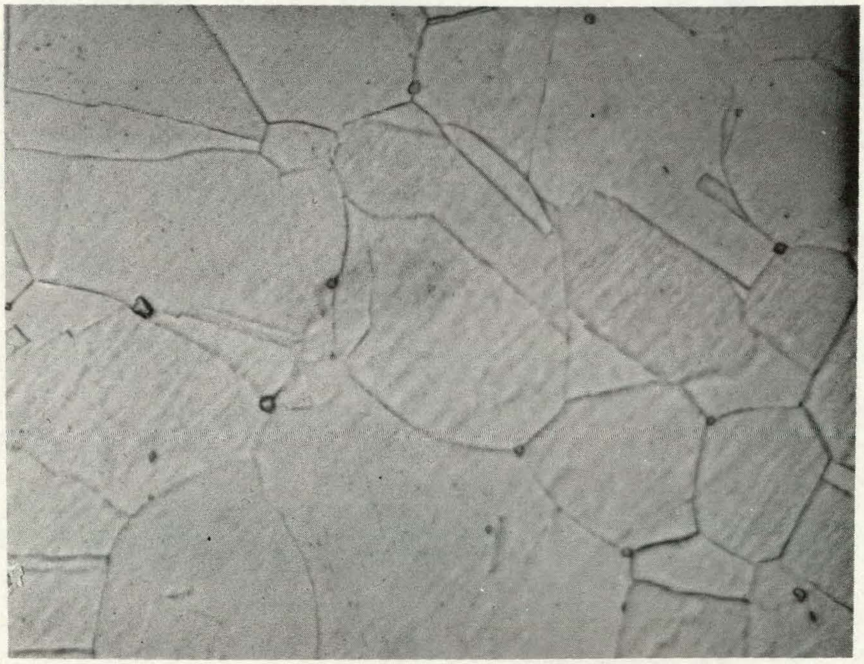
1000X

Bar Stock Used for Upset Forgings

7-1

Bar Stock Used for Die Forgings

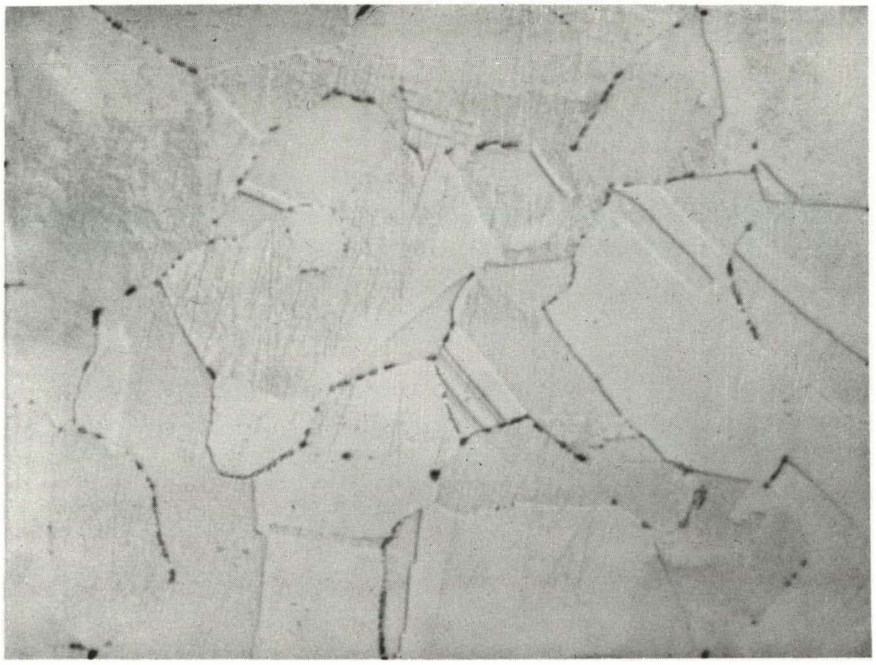
1000X



7-2

FIGURES 7-1 and -2. Photomicrographs of As-Received Bar Stock

FIGURES 8-1 through 8-41.
Photomicrographs of Upset Forgings



Upset Forged at 760 °C
No Anneal

8-1

Specimen 58
Specimens 56 and 21 Similar

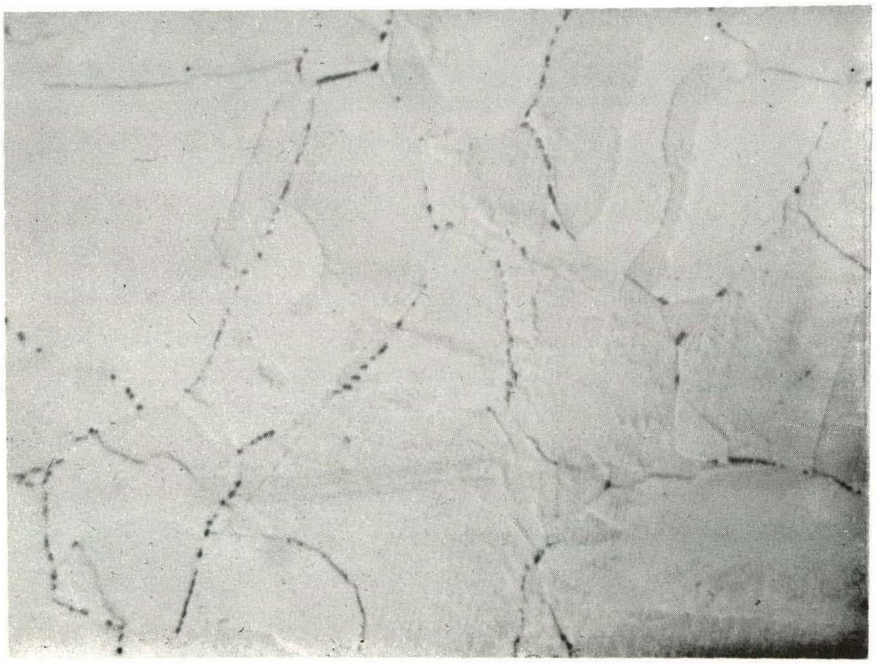
1 Hit-20% Reduction

1000X

Specimen 59
Specimens 23 and 61 Similar

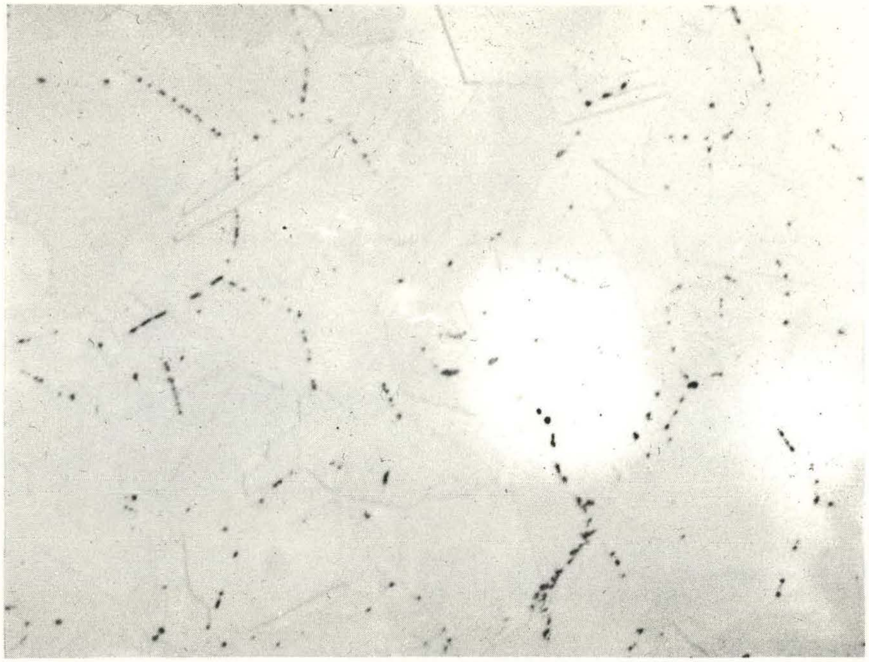
1 Hit-40% Reduction

1000X



Upset Forged at 760 °C
No Anneal

8-2



Upset Forged at 760 °C
Annealed 25 minutes

8-3

Specimen 57
Specimens 55 and 22 Similar

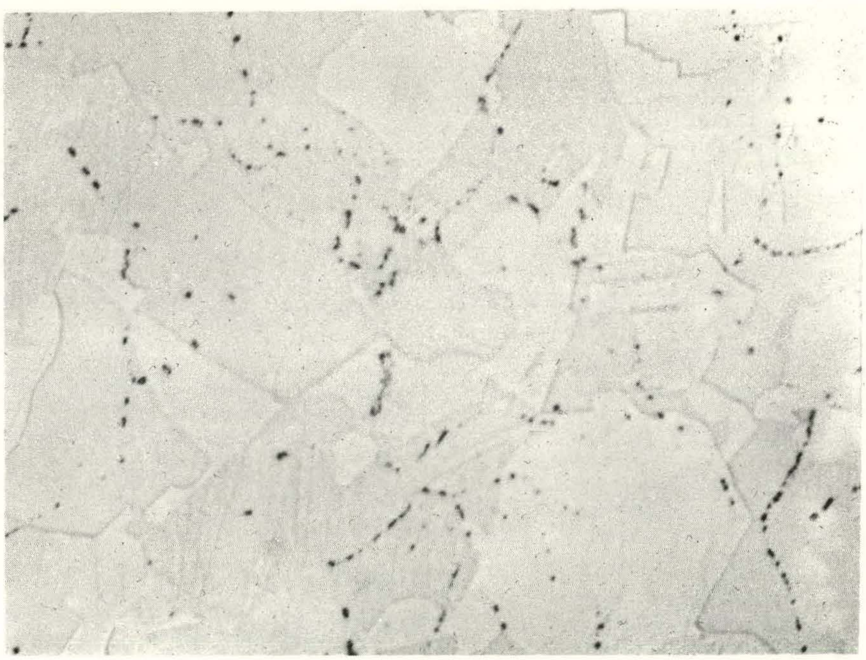
1 Hit-20% Reduction

1000X

Specimen 62
Specimens 60 and 24 Similar

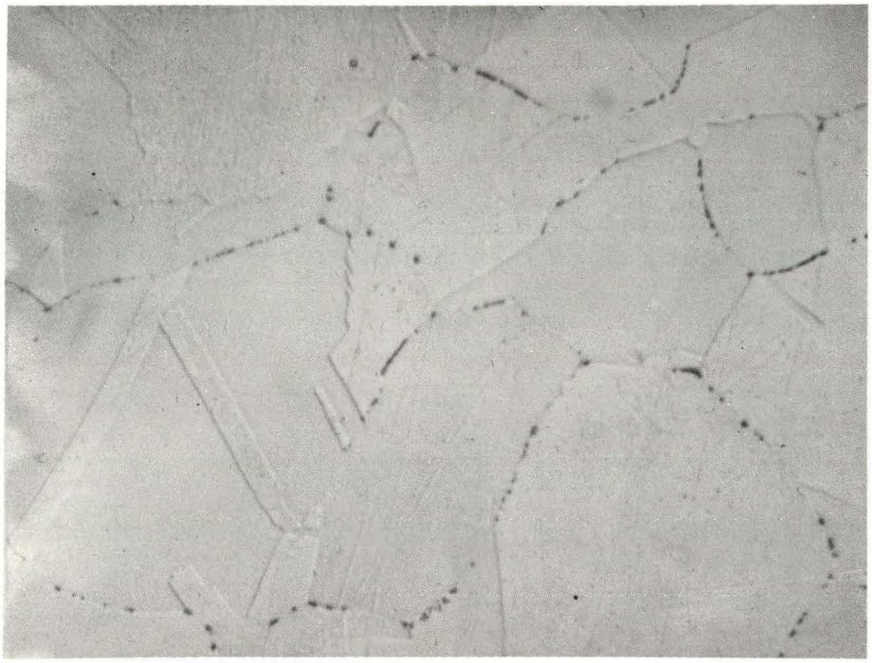
1 Hit-40% Reduction

1000X



Upset Forged at 760 °C
Annealed 25 minutes

8-4

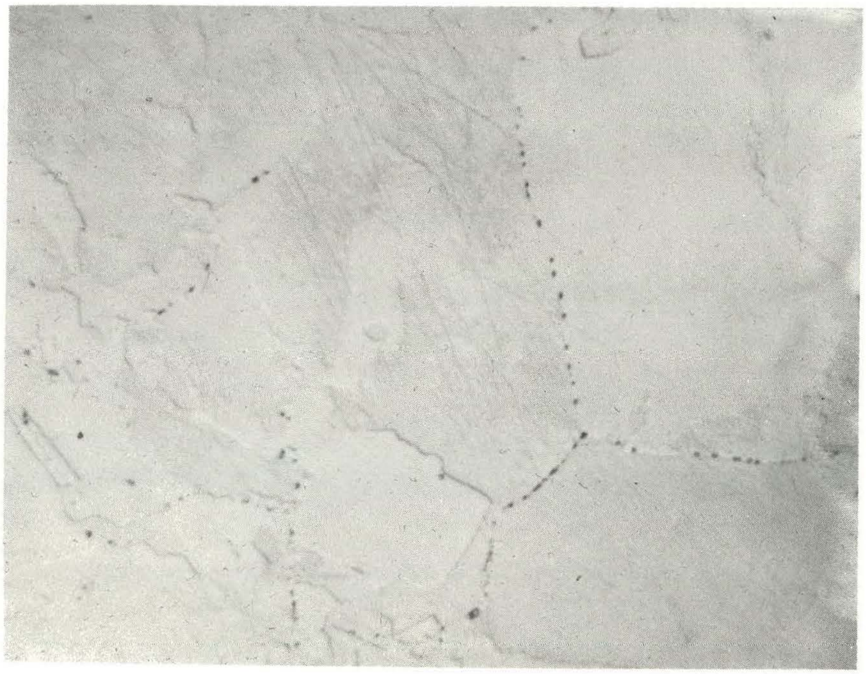


Upset Forged at 860 °C
No Anneal

8-5

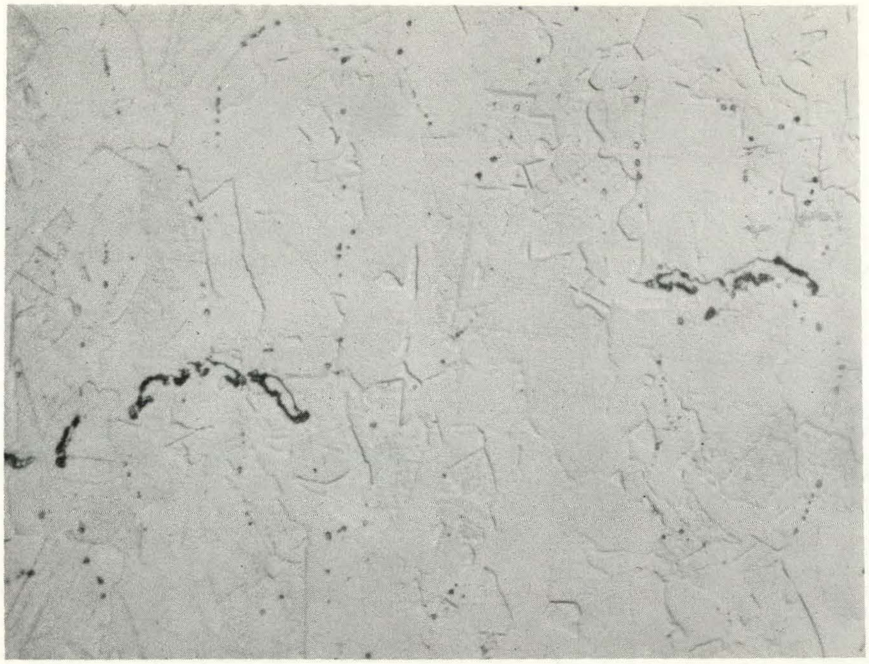
Specimen 28
Specimen 27 Similar
1 Hit-20% Reduction
1000X

Specimen 31
Specimen 33 Similar
1 Hit-40% Reduction
1000X



Upset Forged at 860 °C
No Anneal

8-6



Upset Forged at 860 °C
No Anneal

8-7

Specimen 17
Specimen 19 Similar

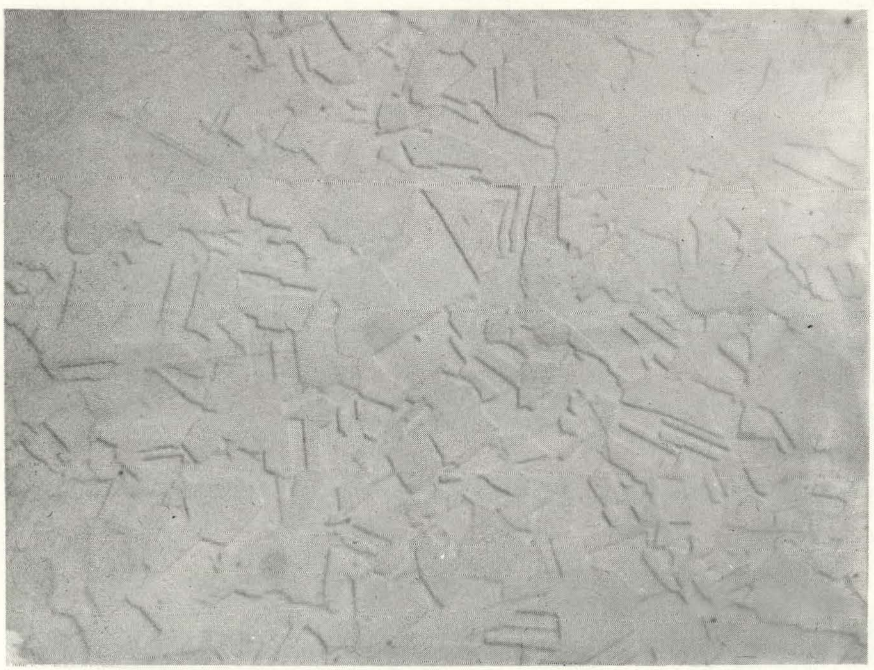
2 Hits-20% Reduction Each

1000X

Specimen 35
Specimens 37 and 38 Similar

1 Hit-60% Reduction

1000X



Upset Forged at 860 °C
No Anneal

8-8

Upset Forged at 860 °C
Annealed 18 minutes

Specimen 36
Specimen 34 Similar

1 Hit-60% Reduction

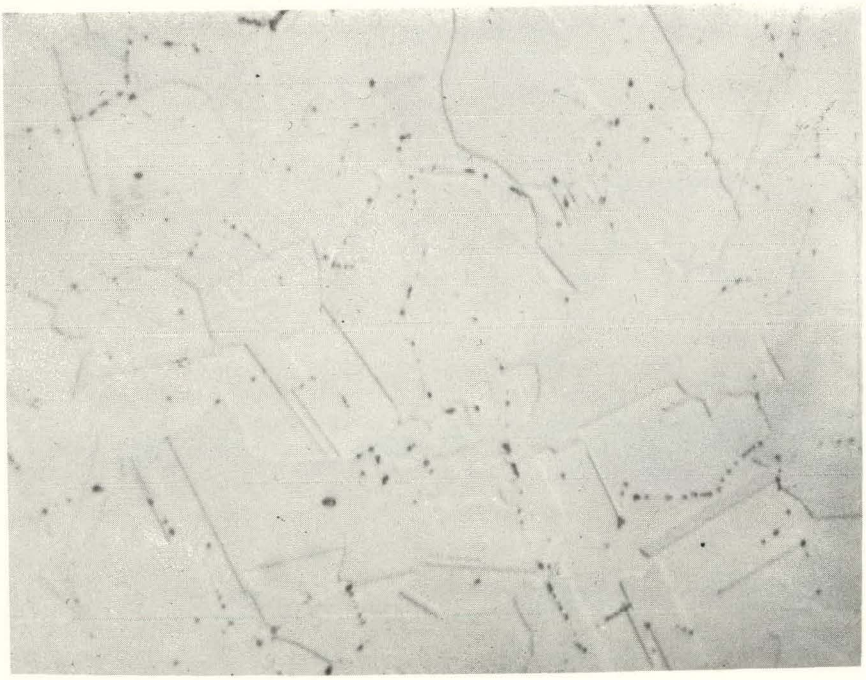
1000X

8-9

Specimen 26
Specimen 29 Similar

1 Hit-20% Reduction

1000X



Upset Forged at 860 °C
Annealed 25 minutes

8-10

Upset Forged at 860 °C
Annealed 25 minutes

8-11

Specimen 30
Specimen 32 Similar

1 Hit-40% Reduction

1000X

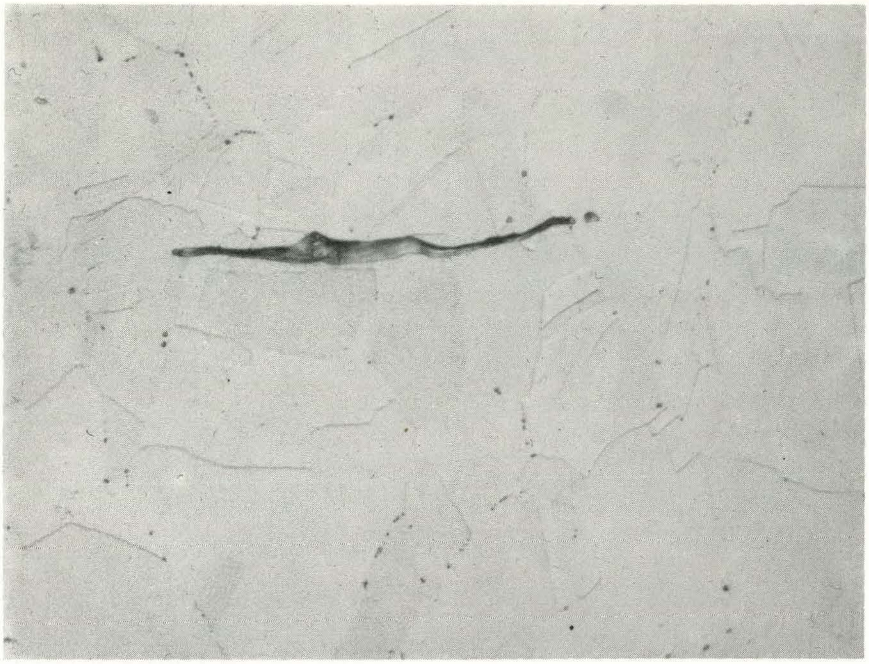
Specimen 20
Specimen 18 Similar

2 Hits-20% Reduction Each

1000X

Upset Forged at 860 °C
Annealed 25 minutes

8-12

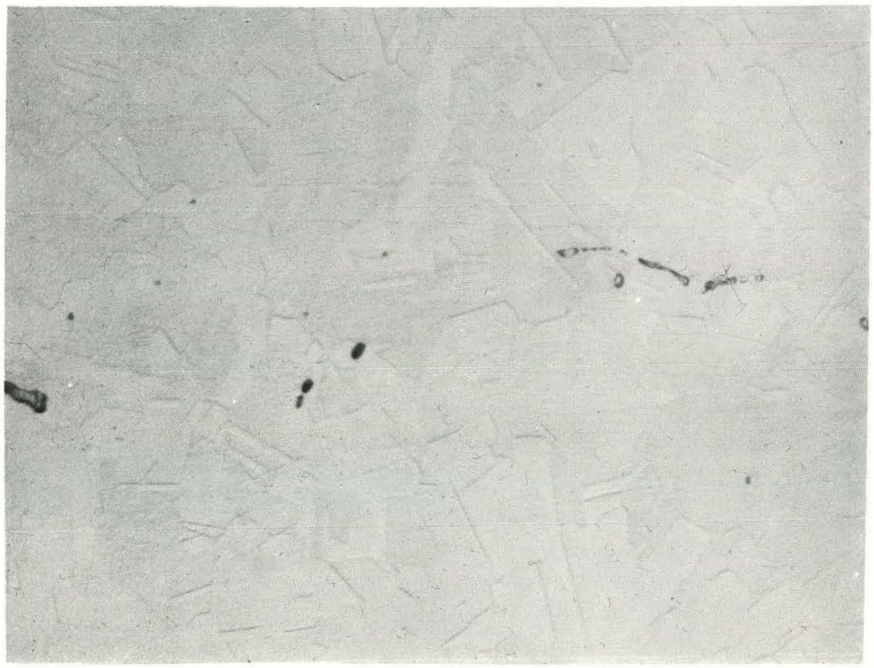


Upset Forged at 900 °C
No Anneal

Specimen 1 1 Hit-20% Reduction 1000X

8-13

Specimen 4 1 Hit-40% Reduction 1000X



Soaked at 900 °C
5-10 minutes
Upset Forged at 900 °C
Water Quenched
No Anneal

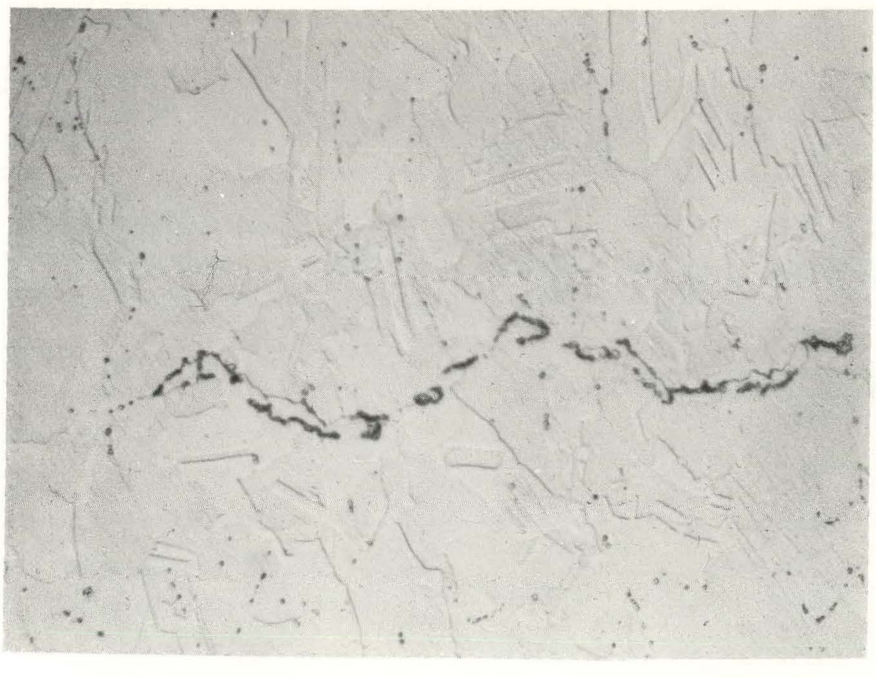
8-14

Soaked at 900 °C
30 minutes
Upset Forged at 900 °C
Water Quenched
No Anneal

8-15

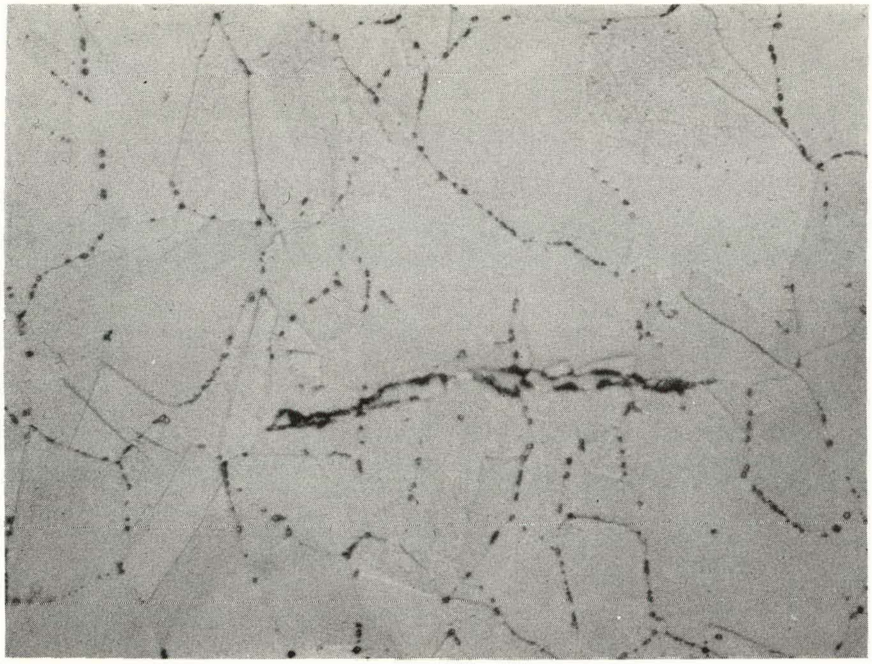
Specimen 25 1 Hit-40% Reduction 1000X

Specimen 7
Specimen 9 Similar 2 Hits-20% Reduction Each 1000X



Upset Forged at 900 °C
No Anneal

8-16

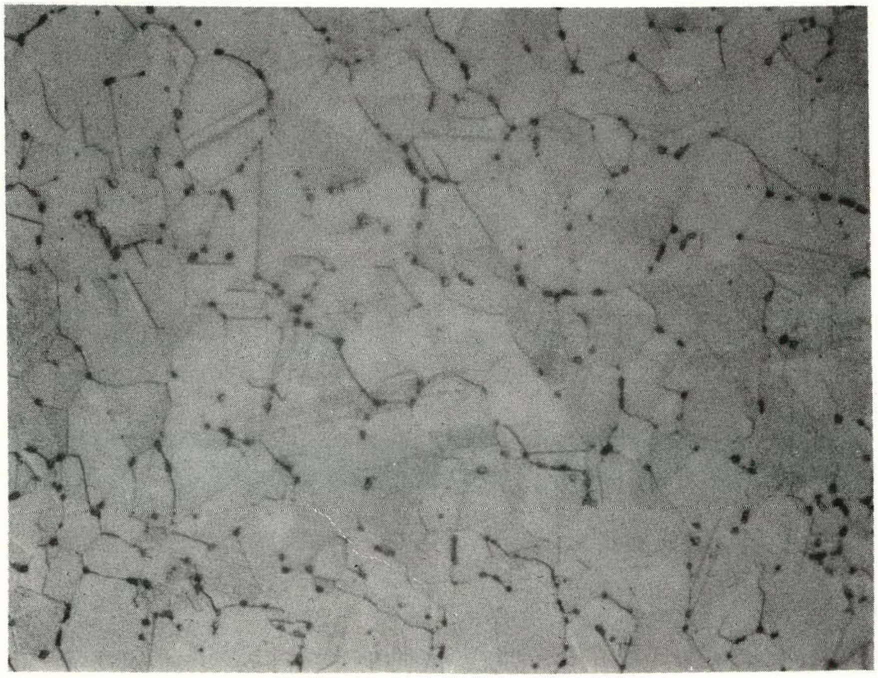


Upset Forged at 900 °C.
Annealed 7½ minutes

8-17

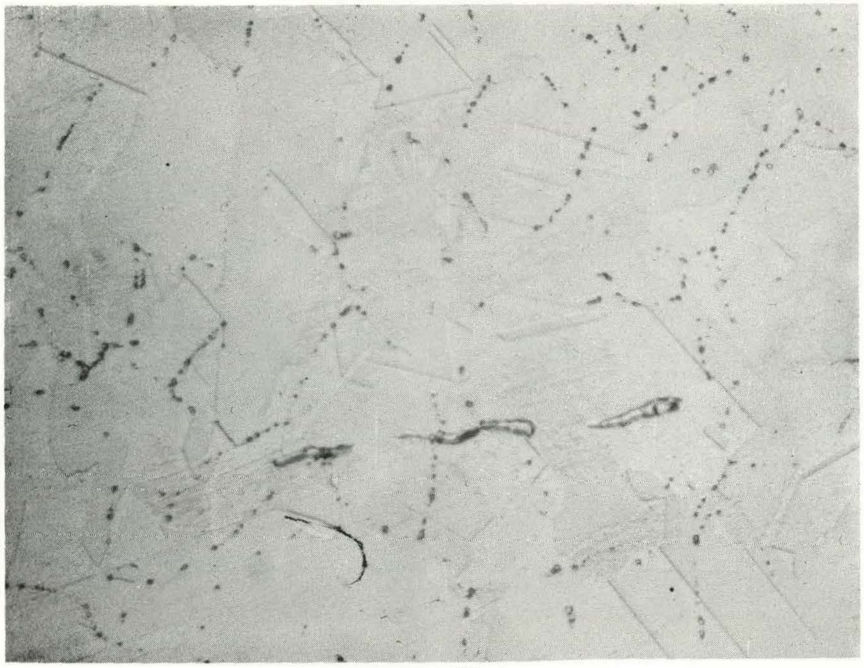
Specimen 2 | 1 Hit-20% Reduction | 1000X

Specimen 5 | 1 Hit-40% Reduction | 1000X



Upset Forged at 900 °C
Annealed 7½ minutes

8-18

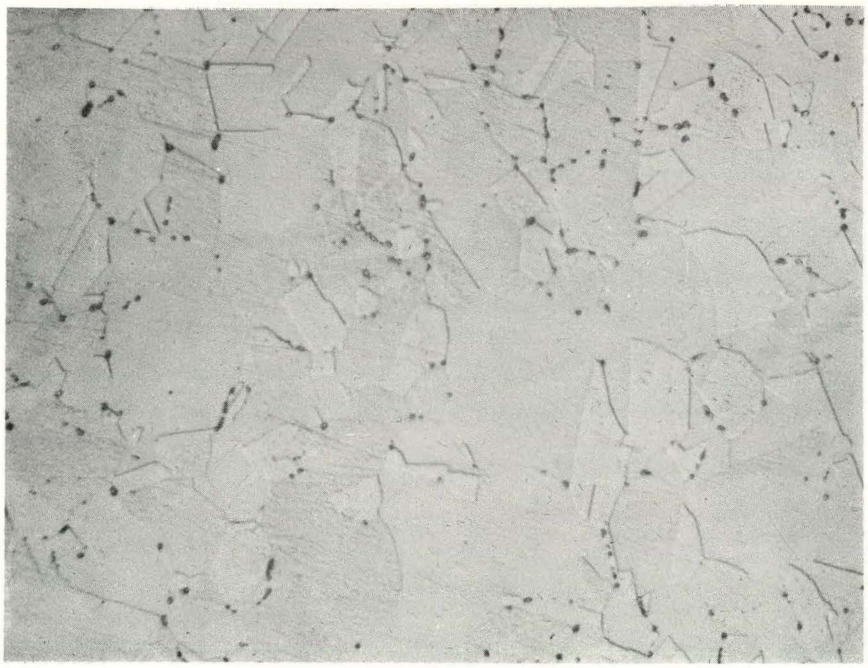


Upset Forged at 900 °C
Annealed 25 minutes

8-19

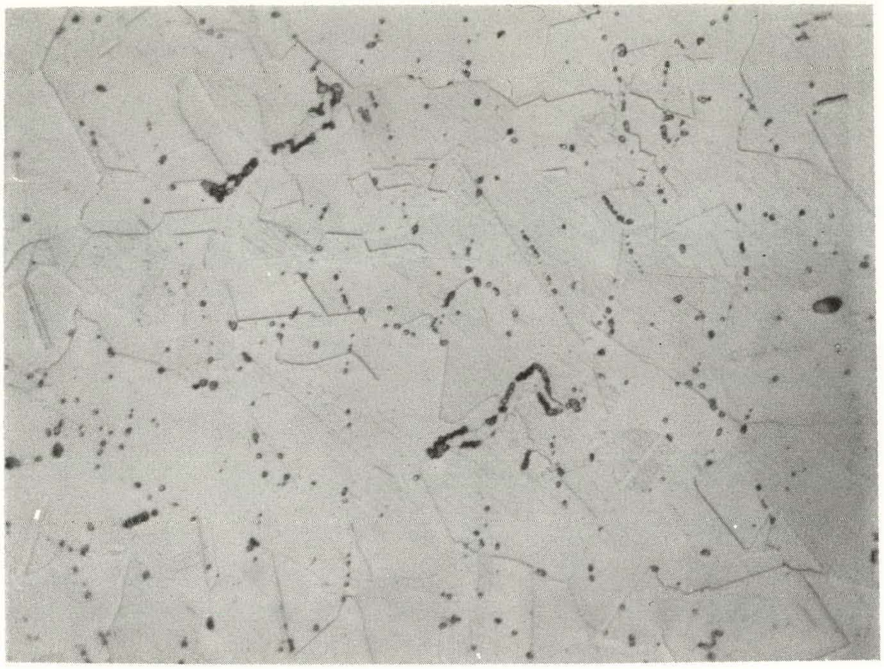
Specimen 3 1 Hit-20% Reduction 1000X

Specimen 6 1 Hit-40% Reduction 1000X



Upset Forged at 900 °C
Annealed 25 minutes

8-20

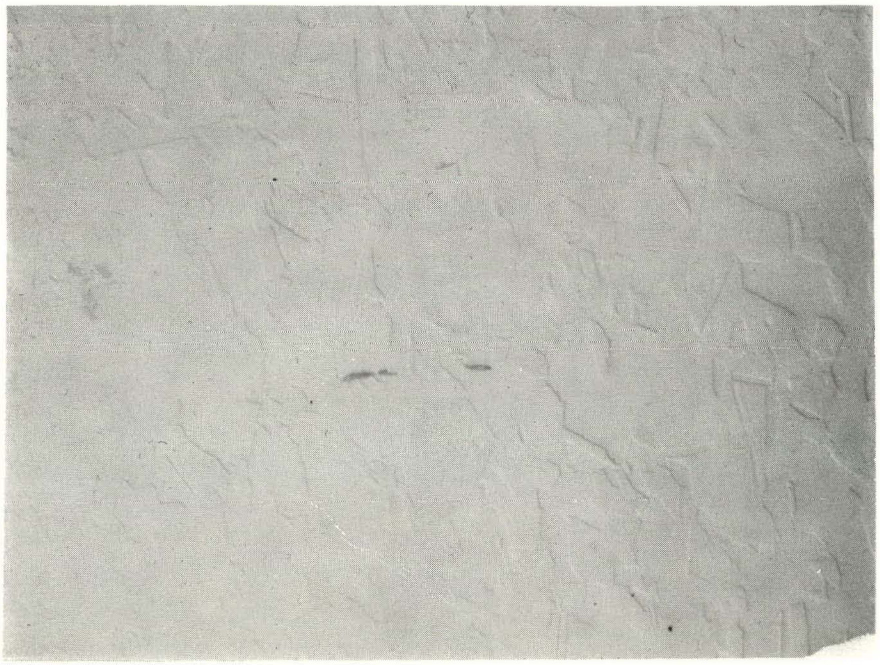


Upset Forged at 900 °C
Annealed 25 minutes

8-21

Specimen 8 2 Hits-20% Reduction Each 1000X
Specimen 10 Similar

Specimen 11 1 Hit-20% Reduction 1000X



Upset Forged at 950 °C
No Anneal

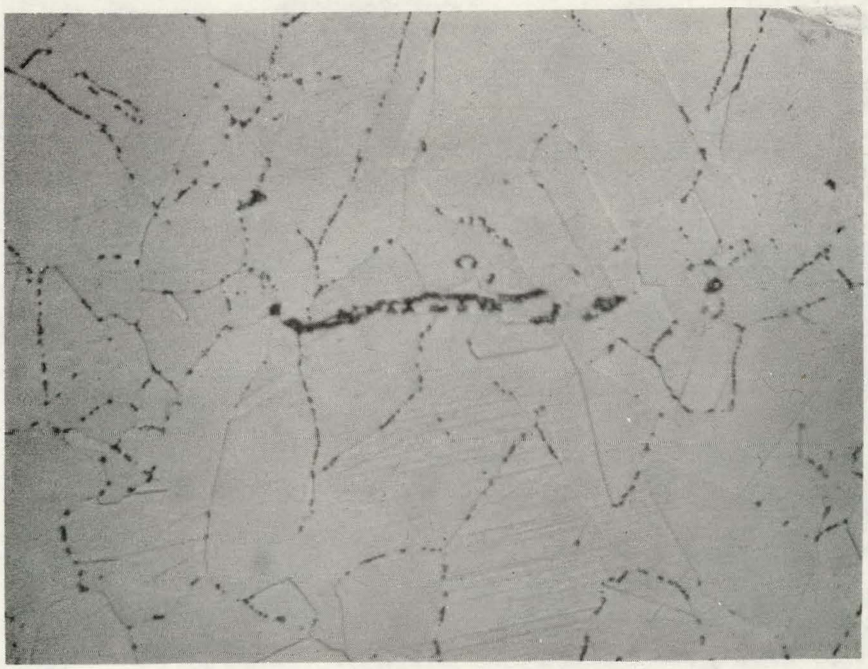
8-22

Upset Forged at 950 °C
No Anneal

8-23

Specimen 14 1 Hit-40% Reduction 1000X

Specimen 12 1 Hit-20% Reduction 1000X



Upset Forged at 950 °C
Annealed 7½ minutes

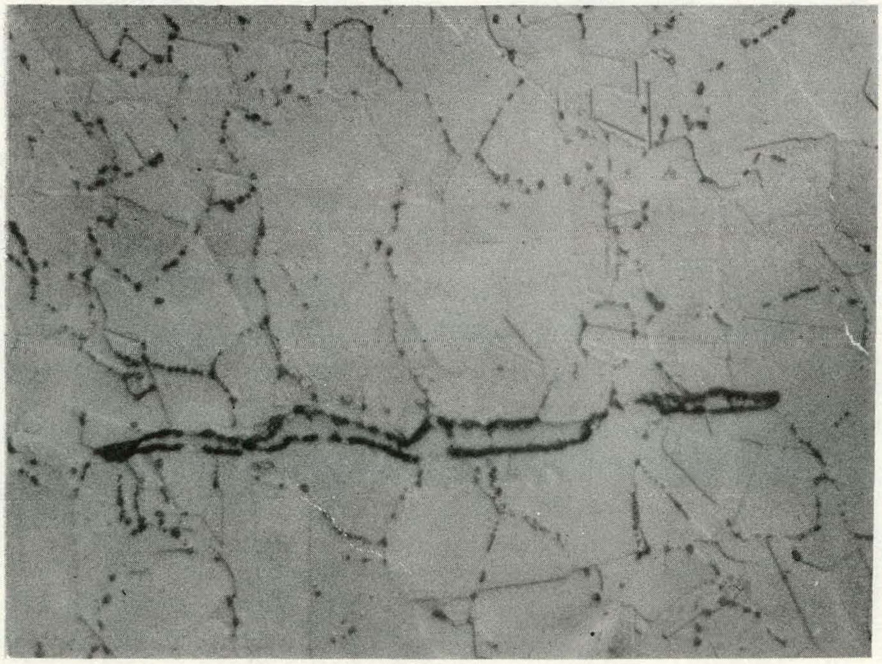
8-24

Upset Forged at 950 °C
Annealed 7½ minutes

Specimen 15 1 Hit-40% Reduction 1000X

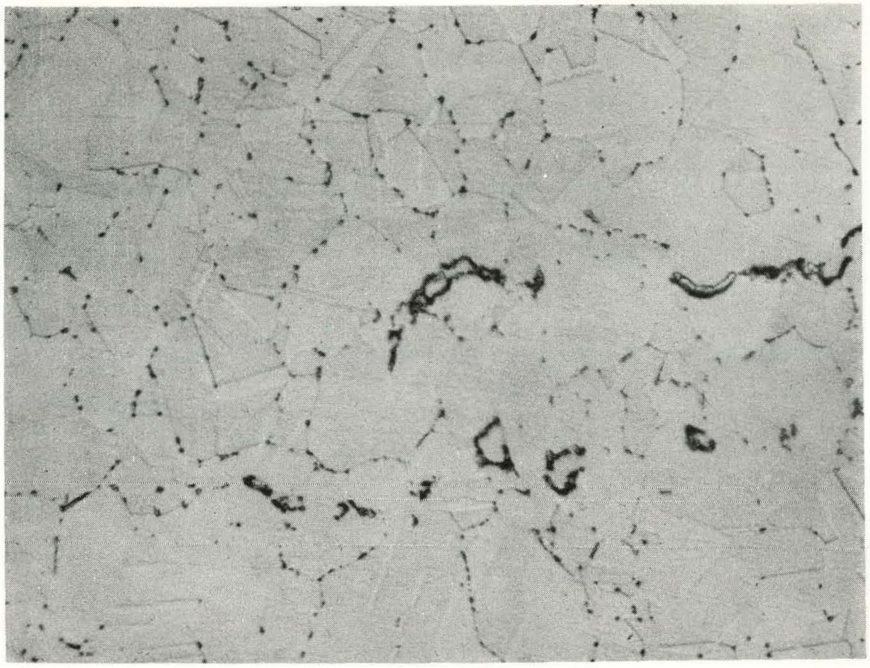
8-25

Specimen 13 1 Hit-20% Reduction 1000X



Upset Forged at 950 °C
Annealed 25 minutes

8-26



Upset Forged at 950 °C
Annealed 25 minutes

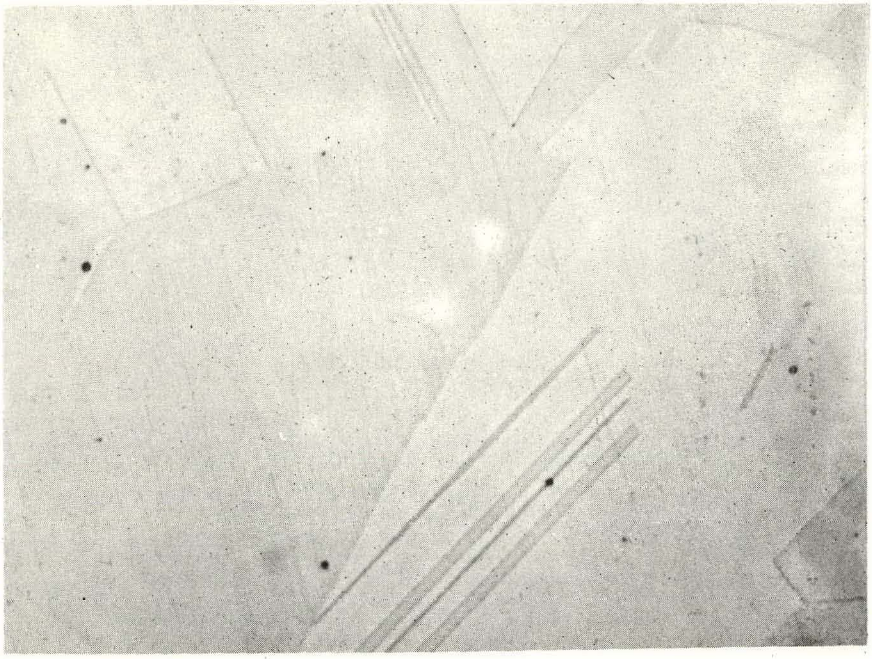
8-27

Specimen 16 1 Hit-40% Reduction 1000X

Specimen 42 1 Hit-20% Reduction 1000X

Upset Forged at 1145 °C
Air Quenched
No Anneal

8-28

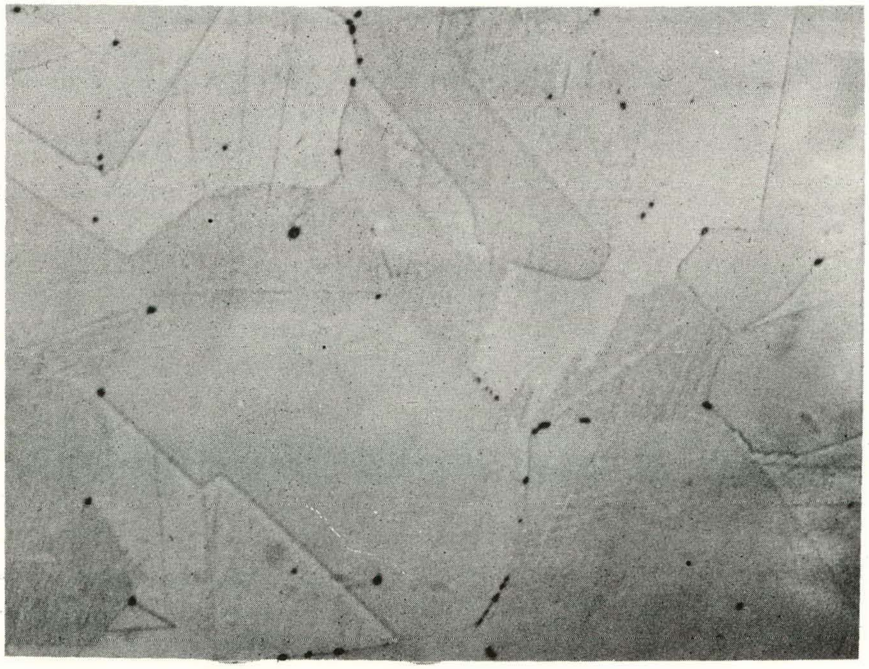


Upset Forged at 1145 °C
Water Quenched
No Anneal

Specimen 40 1 Hit-20% Reduction 1000X

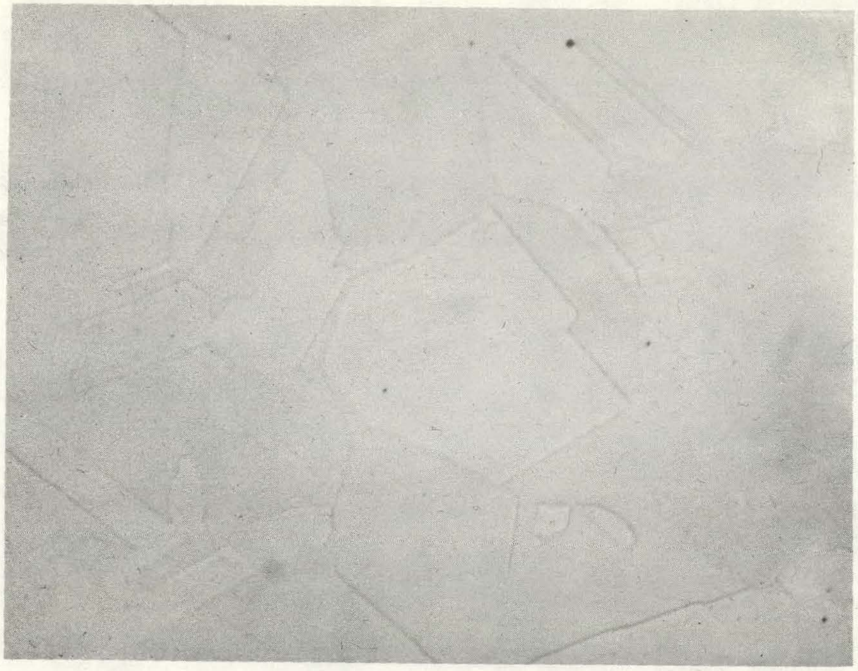
8-29

Specimen 45 1 Hit-40% Reduction 1000X



Upset Forged at 1145 °C
Air Quenched
No Anneal

8-30



Upset Forged at 1145 °C
Water Quenched
No Anneal

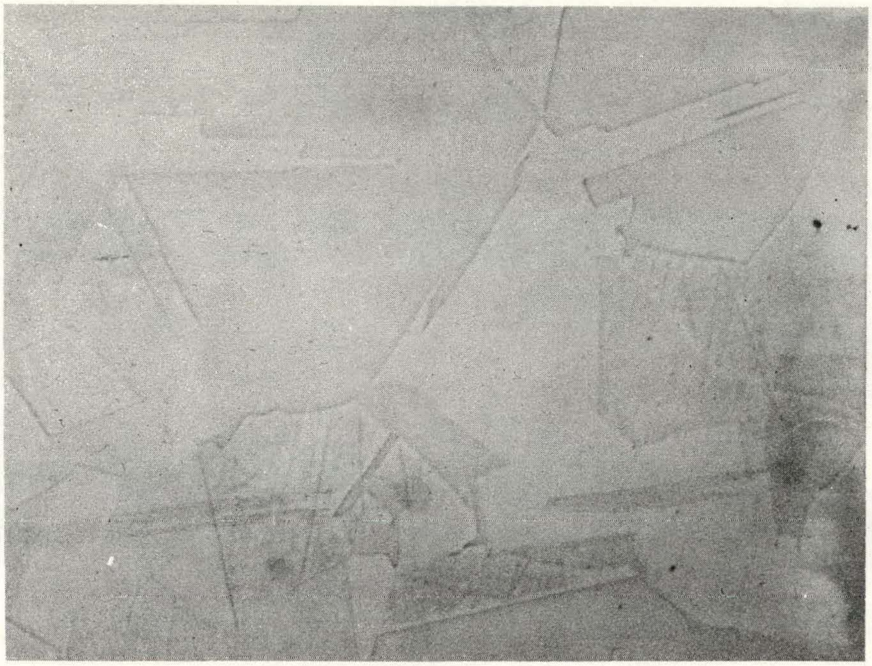
Specimen 43 1 Hit- 40% Reduction 1000X

8-31

Specimen 49 1 Hit-60% Reduction 1000X

Upset Forged at 1145 °C
Air Quenched
No Anneal

8-32

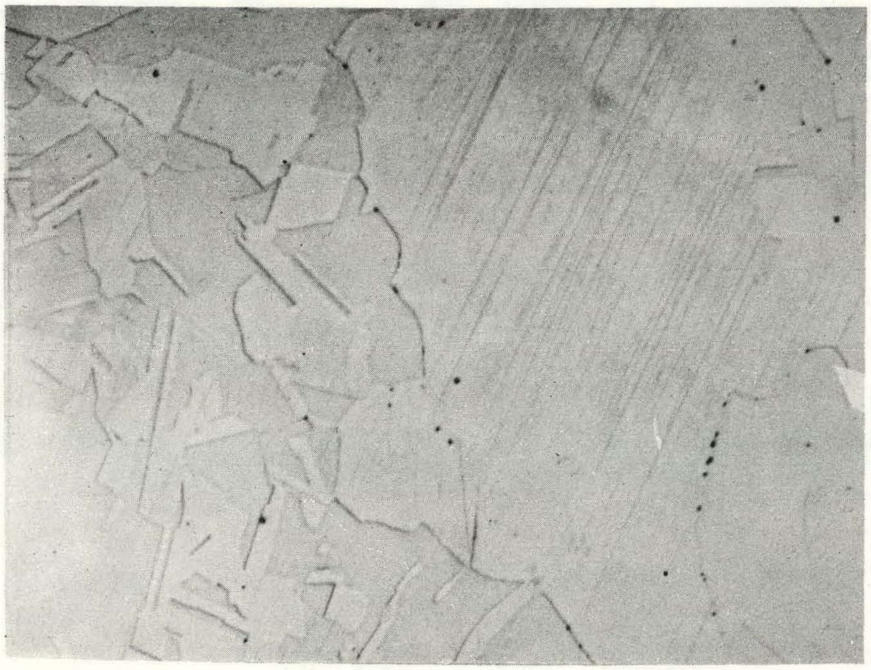


Upset Forged at 1145 °C
Water Quenched
No Anneal

Specimen 48 1 Hit-60% Reduction 1000X

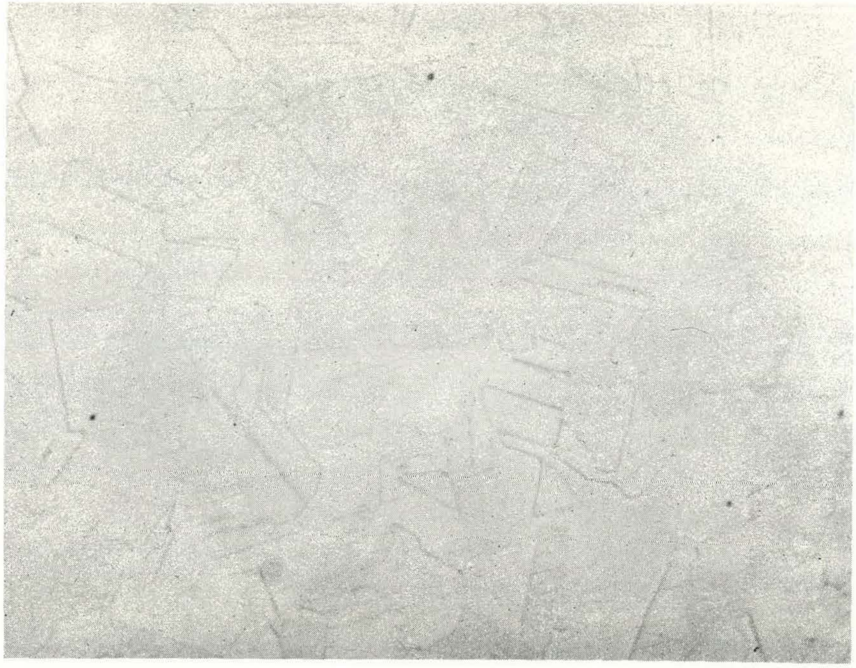
8-33

Specimen 53 3 Hits-20% Reduction Each 1000X



Upset Forged at 1145 °C
Air Quenched
No Anneal

8-34

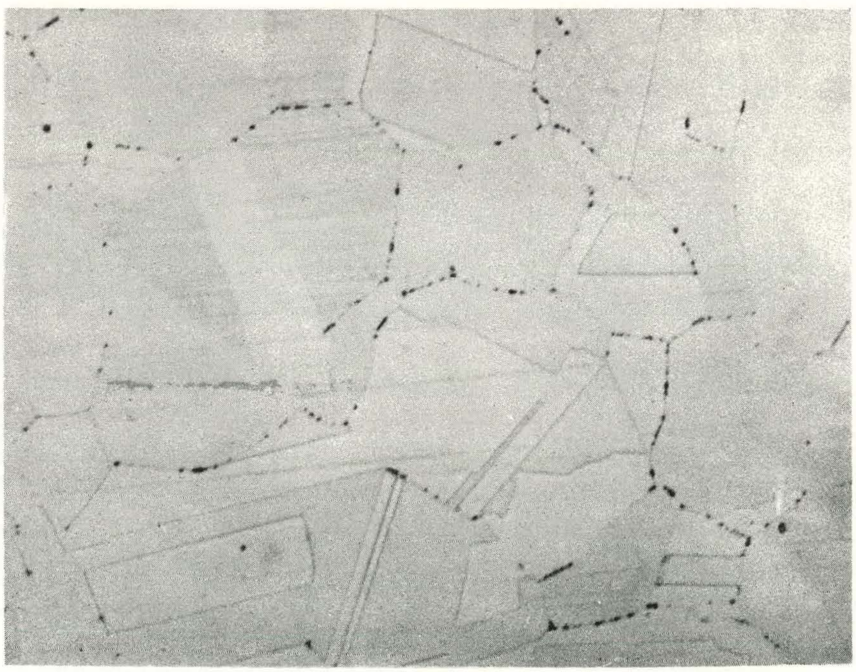


Upset Forged at 1145 °C
Water Quenched
No Anneal

8-35

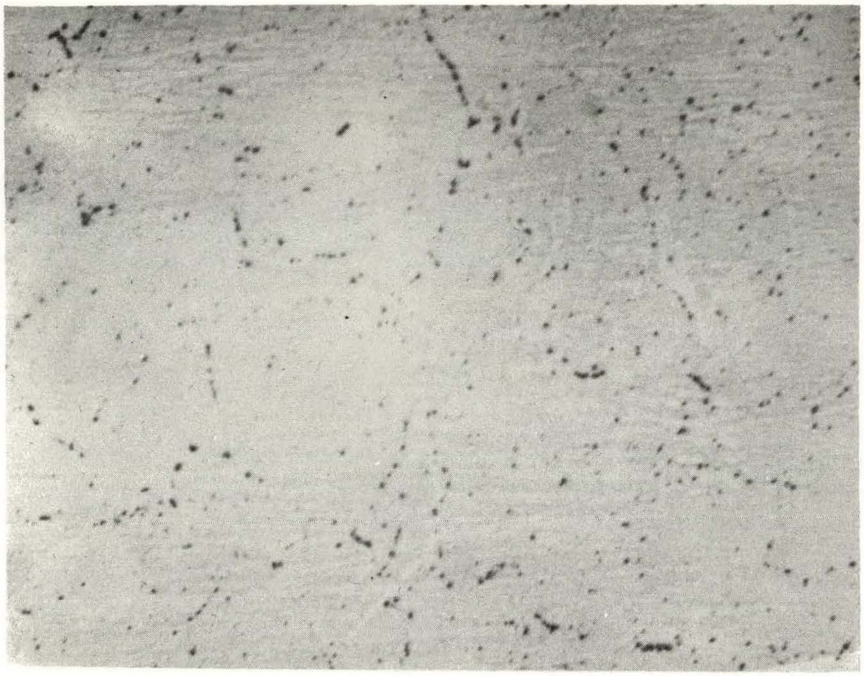
Specimen 52 — 3 Hits-20% Reduction Each — 1000X

Specimen 47
Specimen 50 Similar — 1 Hit-60% Reduction — 1000X



Upset Forged at 1145 °C
Water Quenched
Annealed 18 minutes

8-36

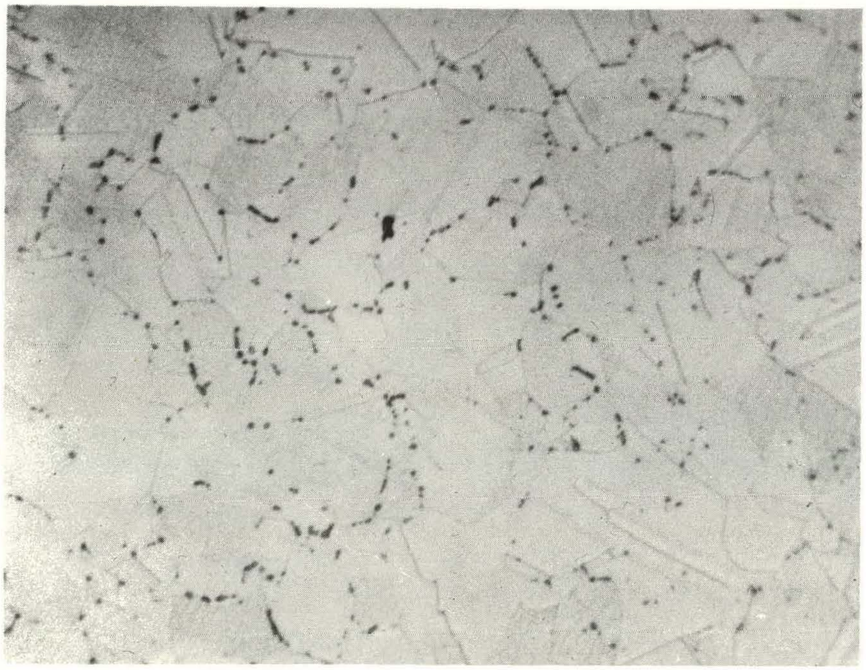


Upset Forged at 1145 °C
Air Quenched
Annealed 18 minutes

Specimen 54 3 Hits-20% Reduction Each 1000X

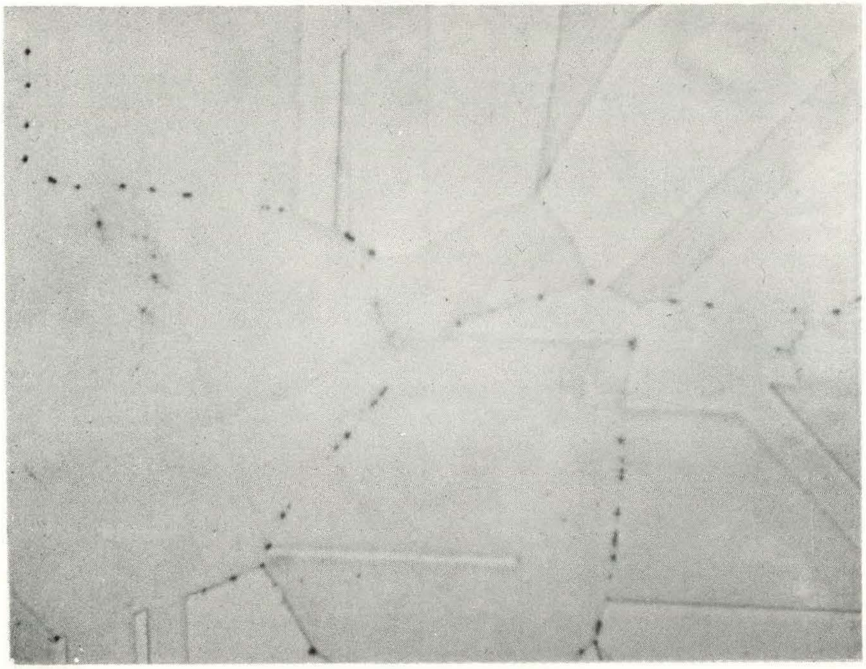
8-37

Specimen 51 3 Hits-20% Reduction Each 1000X



Upset Forged at 1145 °C
Water Quenched
Annealed 18 minutes

8-38



Upset Forged at 1145 °C
Air Quenched
Annealed 25 minutes

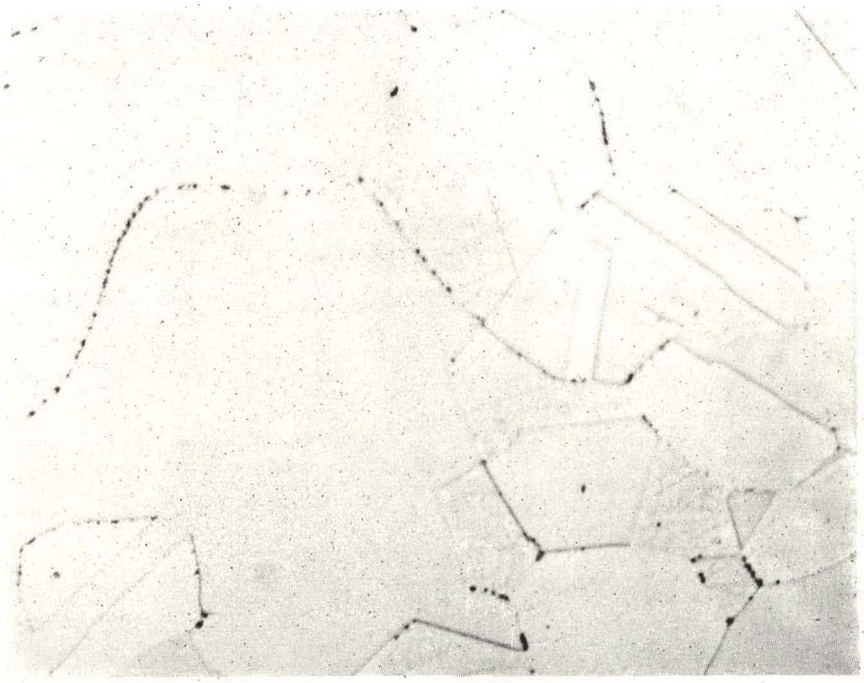
8-39

Specimen 41 1 Hit-20% Reduction 1000X

Specimen 39 1 Hit-20% Reduction 1000X

Upset Forged at 1145 °C
Water Quenched
Annealed 25 minutes

8-40

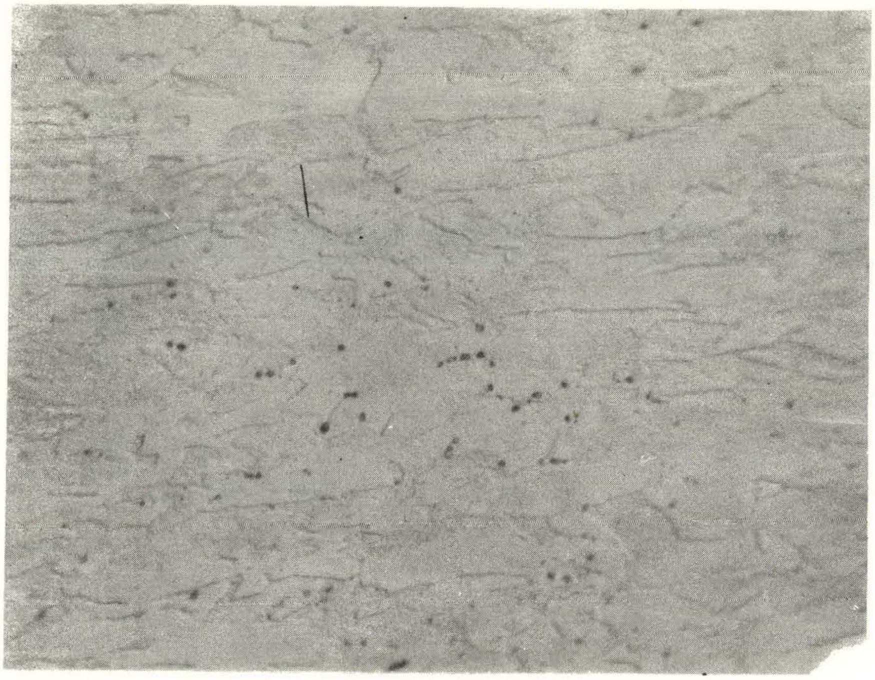


Upset Forged at 1145 °C
Water Quenched
Annealed 25 minutes

8-41

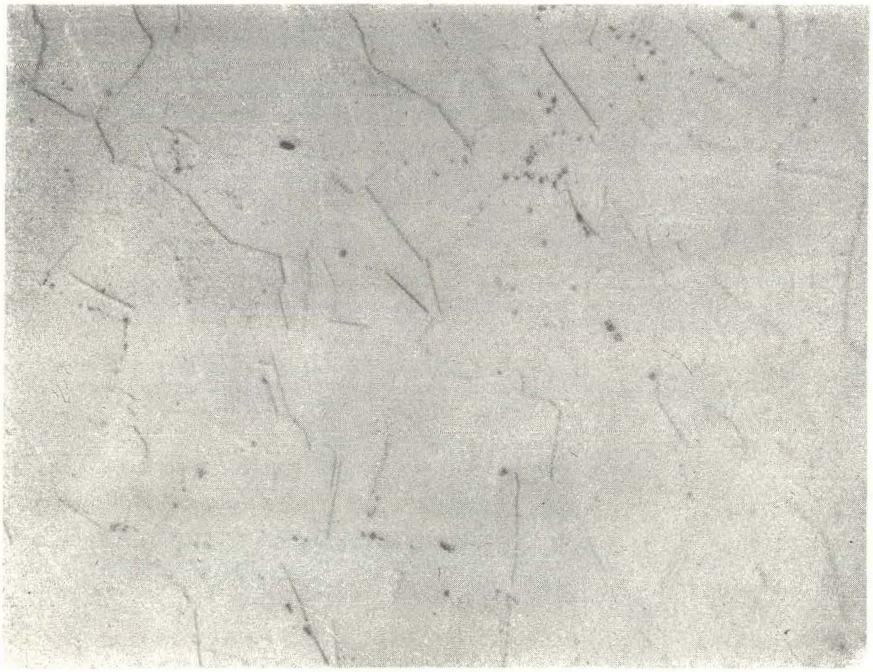
Specimen 44 1 Hit-40% Reduction 1000X
Specimen 45 Similar

FIGURES 9-1 through 9-12. →
Photomicrographs of Die Forgings



Specimen C Hammer 1000X

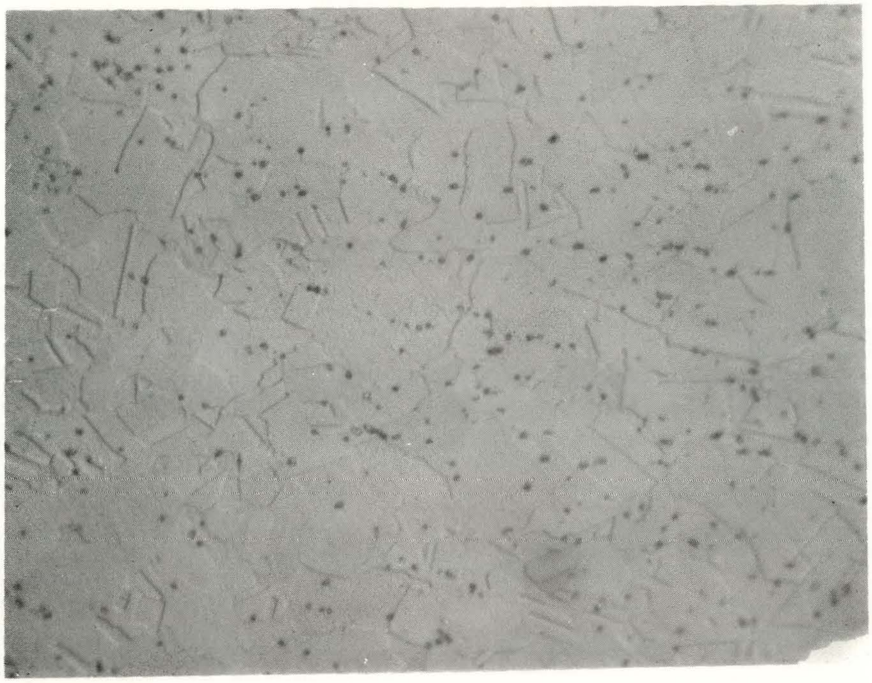
Specimen K Dynapak 1000X



Soaked at 900 °C
5 minutes
Hit 1 at 900 °C
Water Quenched
Soaked at 900 °C
5 minutes
Air Cooled to 760 °C
Hit 2 at 760 °C
Water Quenched
No Anneal

9-1

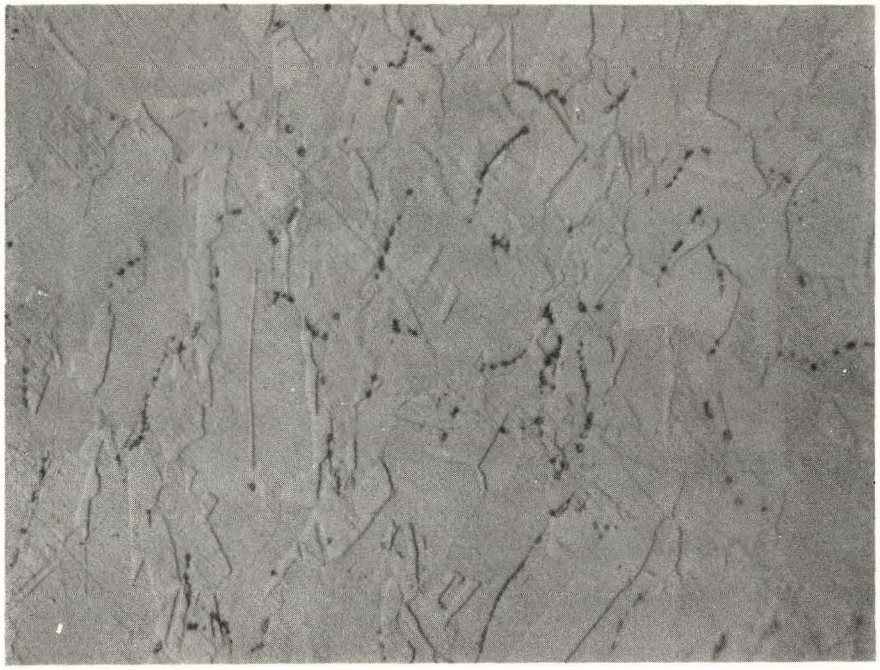
FIGURES 9-1 through 9-12. Photomicrographs of Die Forgings



Specimen CA Hammer 1000X

Soaked at 900 °C
5 minutes
Hit 1 at 900 °C
Water Quenched
Soaked at 900 °C
5 minutes
Air Cooled to 760 °C
Hit 2 at 760 °C
Water Quenched
Annealed 7½ minutes

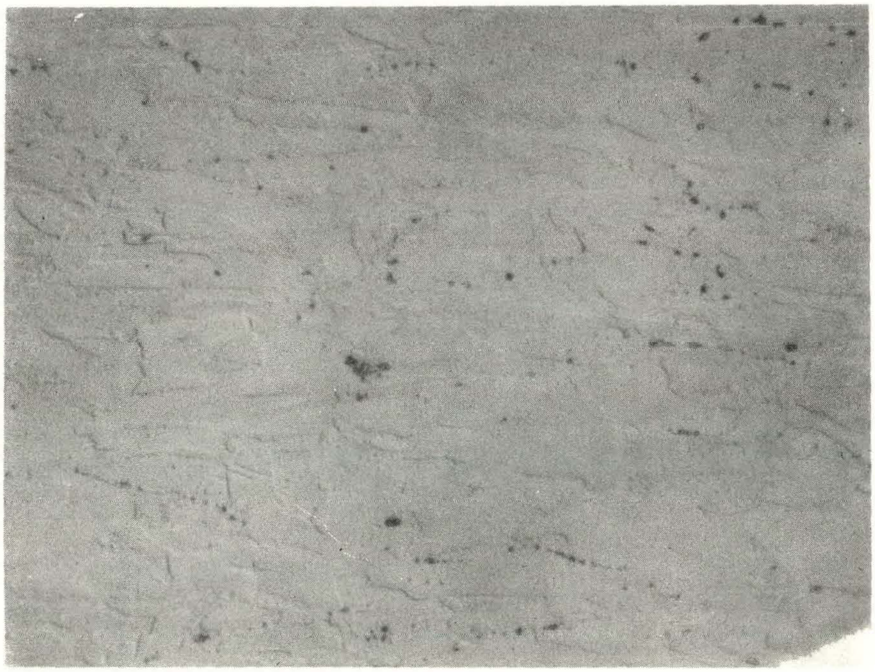
Specimen KA Dynapak 1000X



Specimen E Hammer 1000X

Soaked at 860 °C
5 minutes
Hit 1 at 860 °C
No Quench
Soaked at 860 °C
5 minutes
Hit 2 at 860 °C
Water Quenched
No Anneal

Specimen L Dynapak 1000X

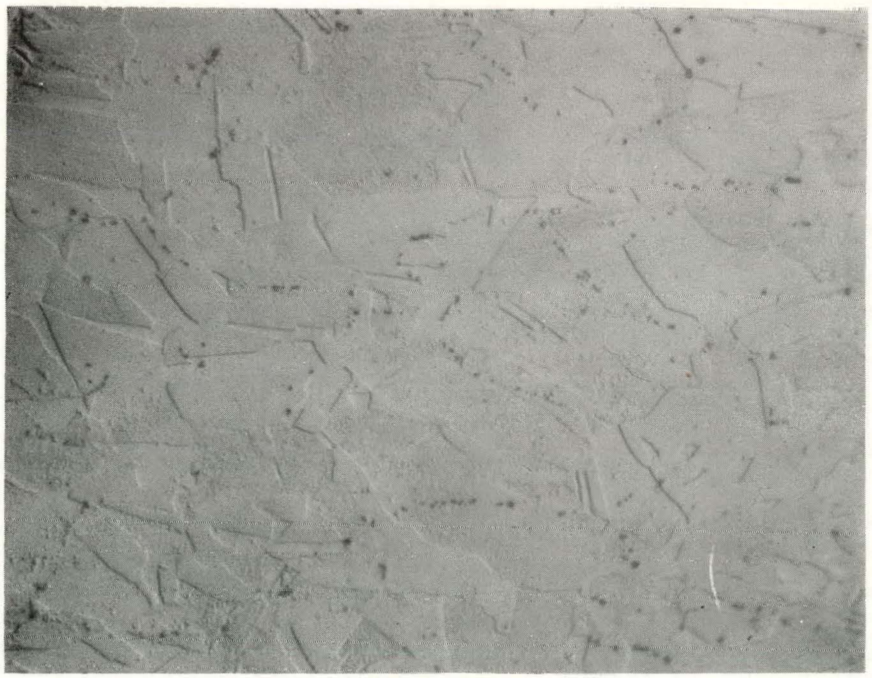


9-3

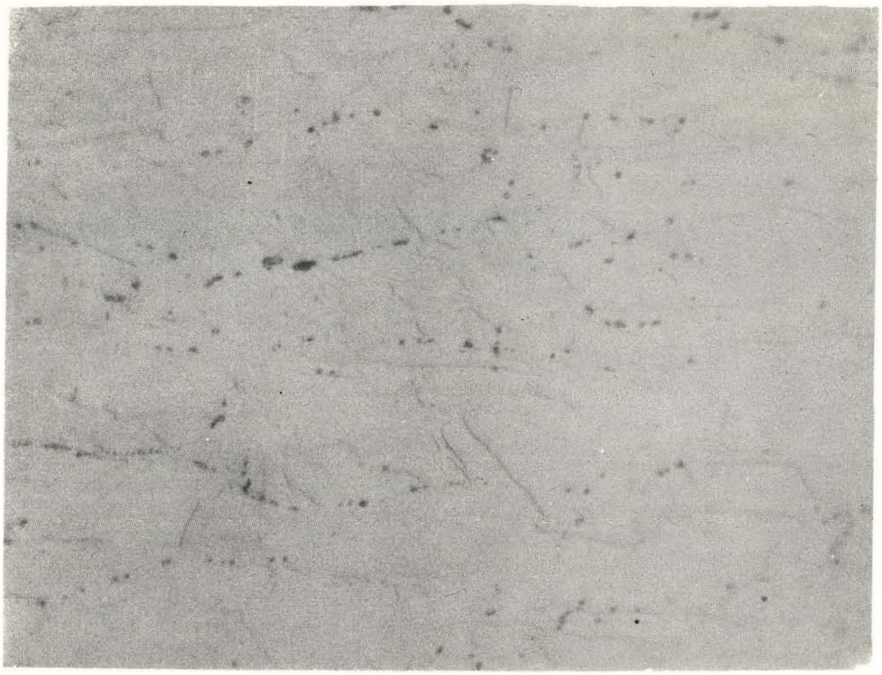
Specimen A Hammer 1000X

Soaked at 860 °C
5 minutes
Hit 1 860 °C
Water Quenched
Soaked at 860 °C
5 minutes
Hit 2 at 860 °C
Water Quenched
No Anneal

Specimen G Dynapak 1000X



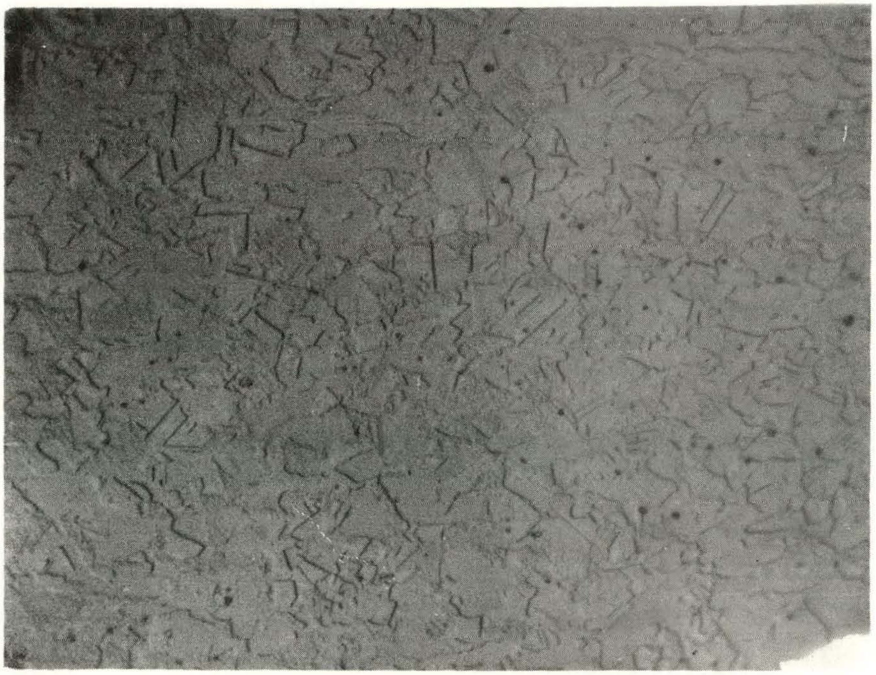
9-4



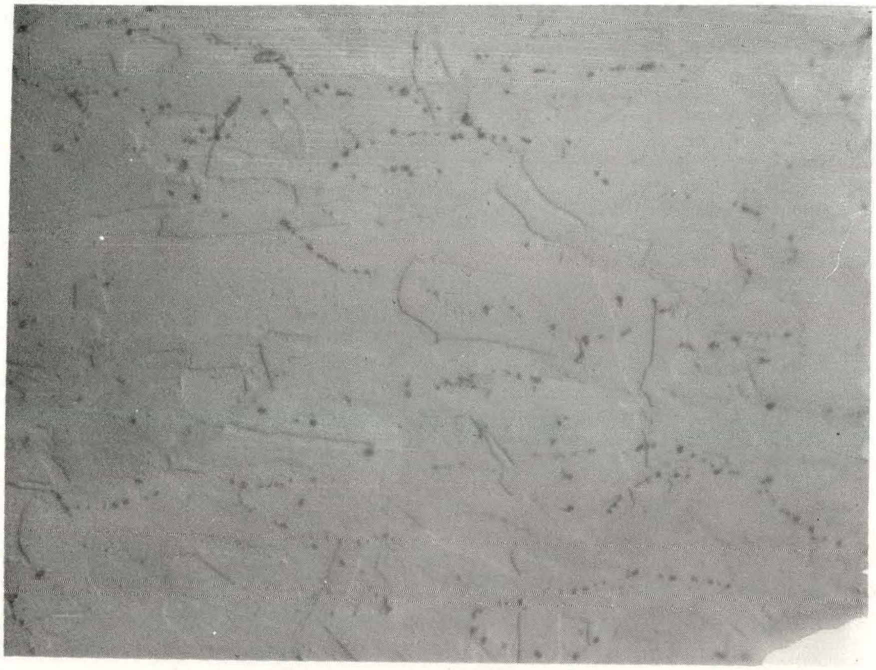
Specimen D Hammer 1000X

Soaked at 860 °C
30 minutes
Hit 1 at 860 °C
Water Quenched
Soaked at 860 °C
5 minutes
Hit 2 at 860 °C
Water Quenched
No Anneal

Specimen H Dynapak 1000X



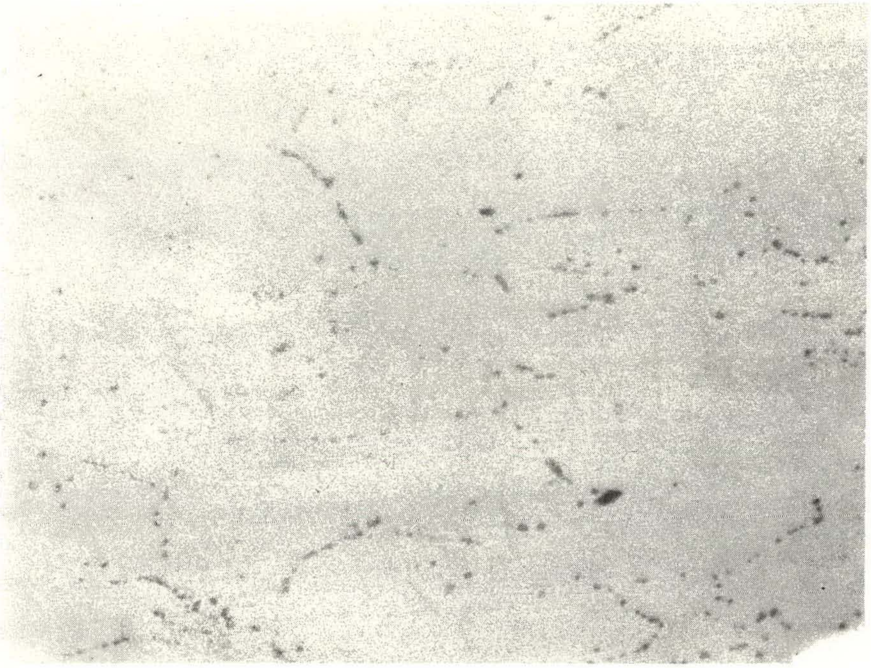
9-5



Soaked at 860 °C
30 minutes
Hit 1 at 860 °C
Water Quenched
Soaked at 860 °C
30 minutes
Hit 2 at 860 °C
Water Quenched
No Anneal

Specimen I **Dynapak** **1000X**

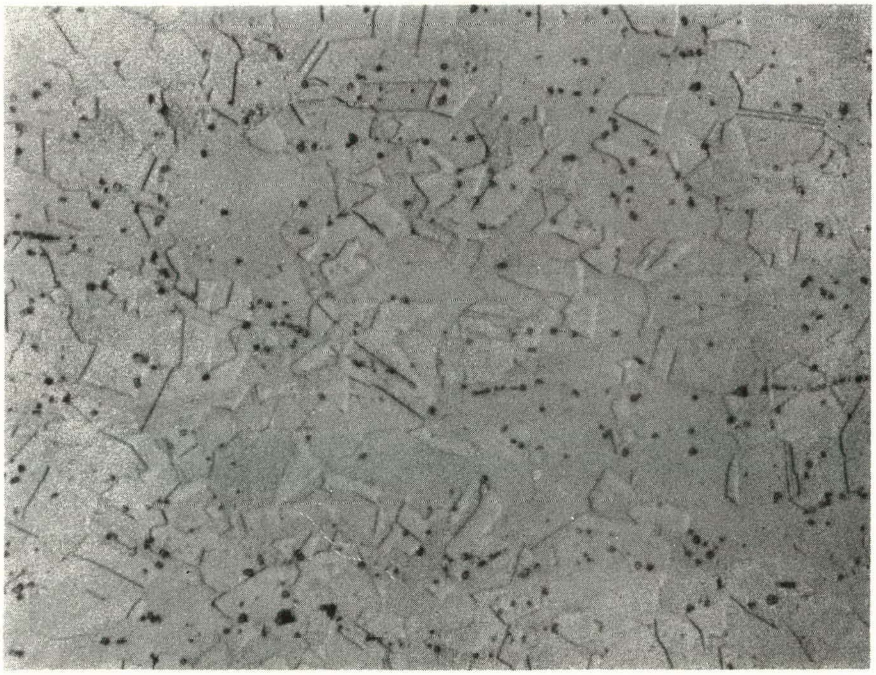
9-6



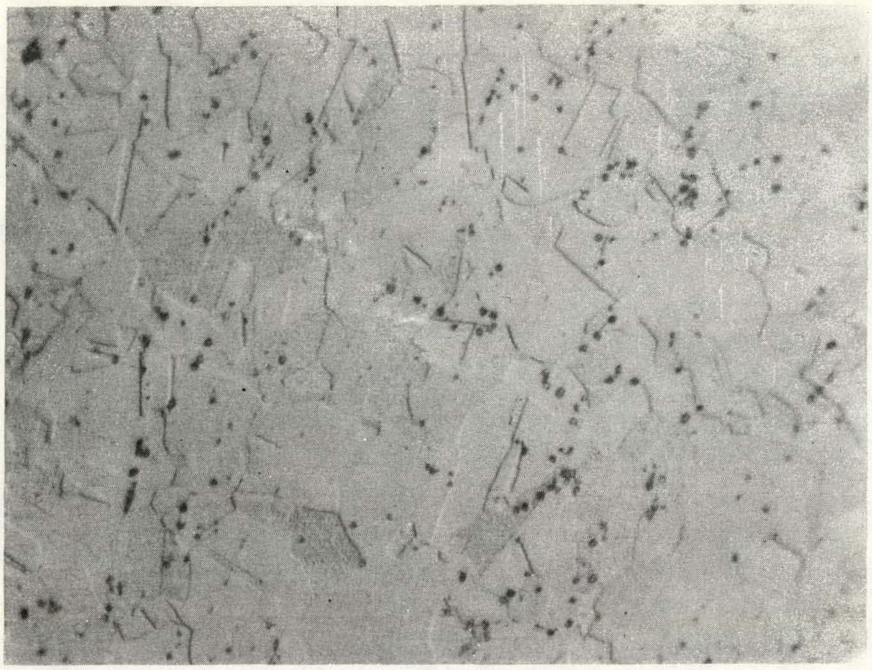
Specimen EA Hammer 1000X

Soaked at 860 °C
5 minutes
Hit 1 at 860 °C
No Quench
Soaked at 860 °C
5 minutes
Hit 2 at 860 °C
Water Quenched
Annealed 7½ minutes

Specimen LA Dynapak 1000X



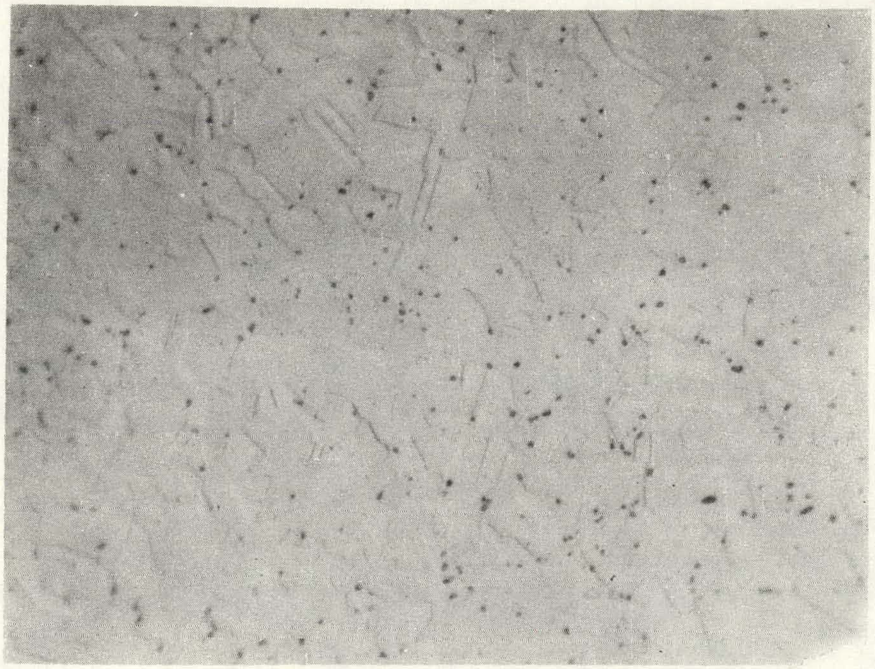
9-7



Specimen AA Hammer 1000X

Soaked at 860 °C
5 minutes
Hit 1 at 860 °C
Water Quenched
Soaked at 860 °C
5 minutes
Hit 2 at 860 °C
Water Quenched
Annealed 7½ minutes

Specimen GA Dynapak 1000X

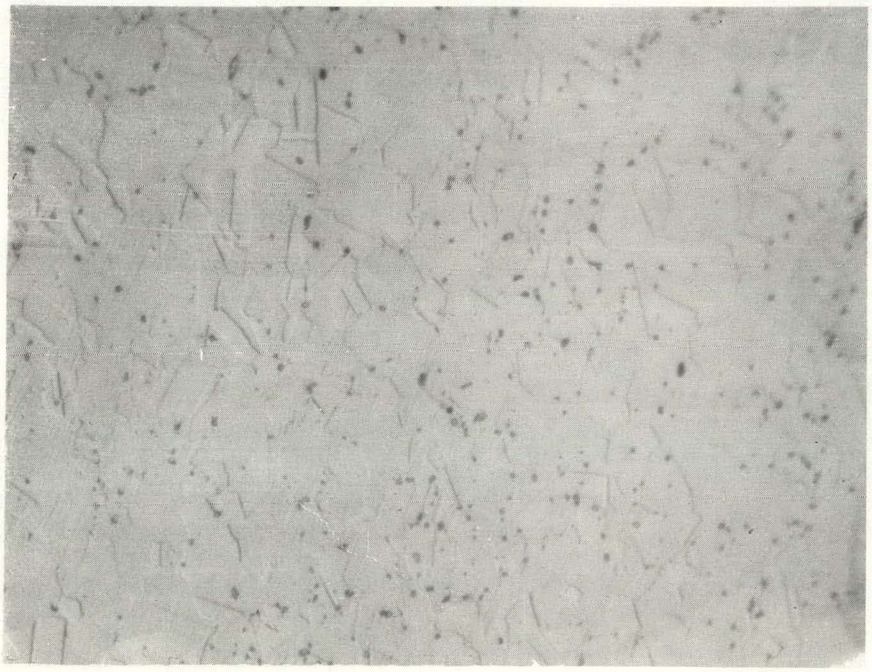


9-8

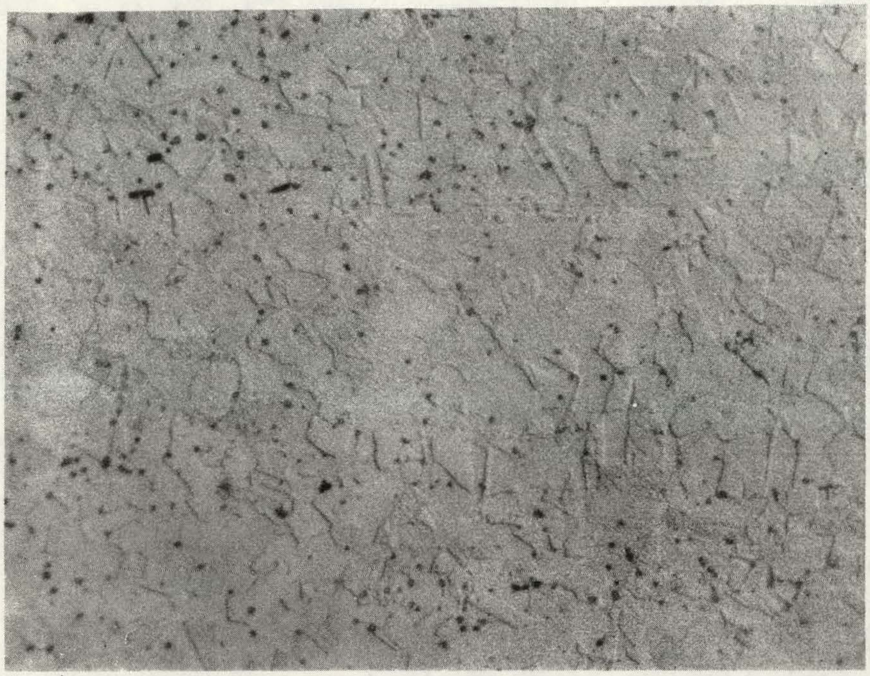
Specimen DA   Hammer   1000X

Soaked at 860 °C
30 minutes
Hit 1 at 860 °C
Water Quenched
Soaked at 860 °C
5 minutes
Hit 2 at 860 °C
Water Quenched
Annealed 7½ minutes

Specimen HA   Dynapak   1000X



9-9



Soaked at 860 °C
30 minutes
Hit 1 at 860 °C
Water Quenched
Soaked at 860 °C
30 minutes
Hit 2 at 860 °C
Water Quenched
Annealed 7½ minutes

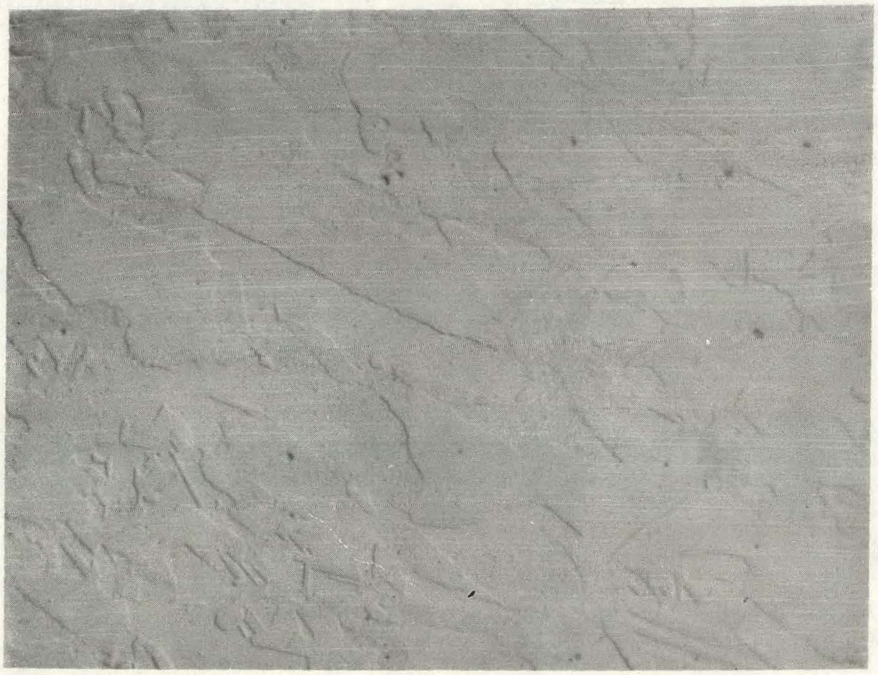
Specimen IA **Dynapak** **1000X**

9-10

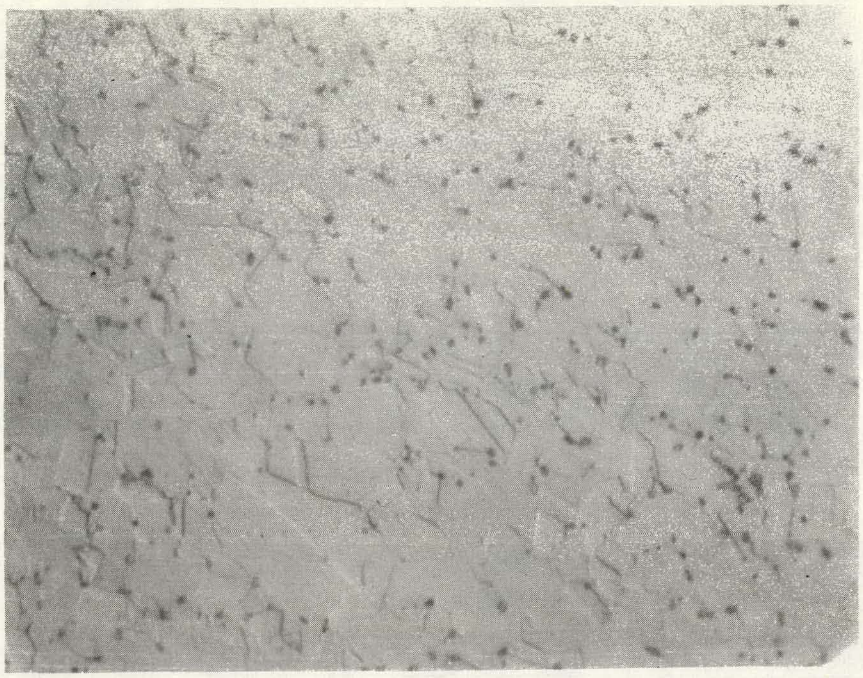
Specimen B Hammer 1000X

Soaked at 950 °C
5 minutes
Hit 1 at 950 °C
Water Quenched
Soaked at 950 °C
5 minutes
Hit 2 at 950 °C
Water Quenched
No Anneal

Specimen J Dynapak 1000X



9-11

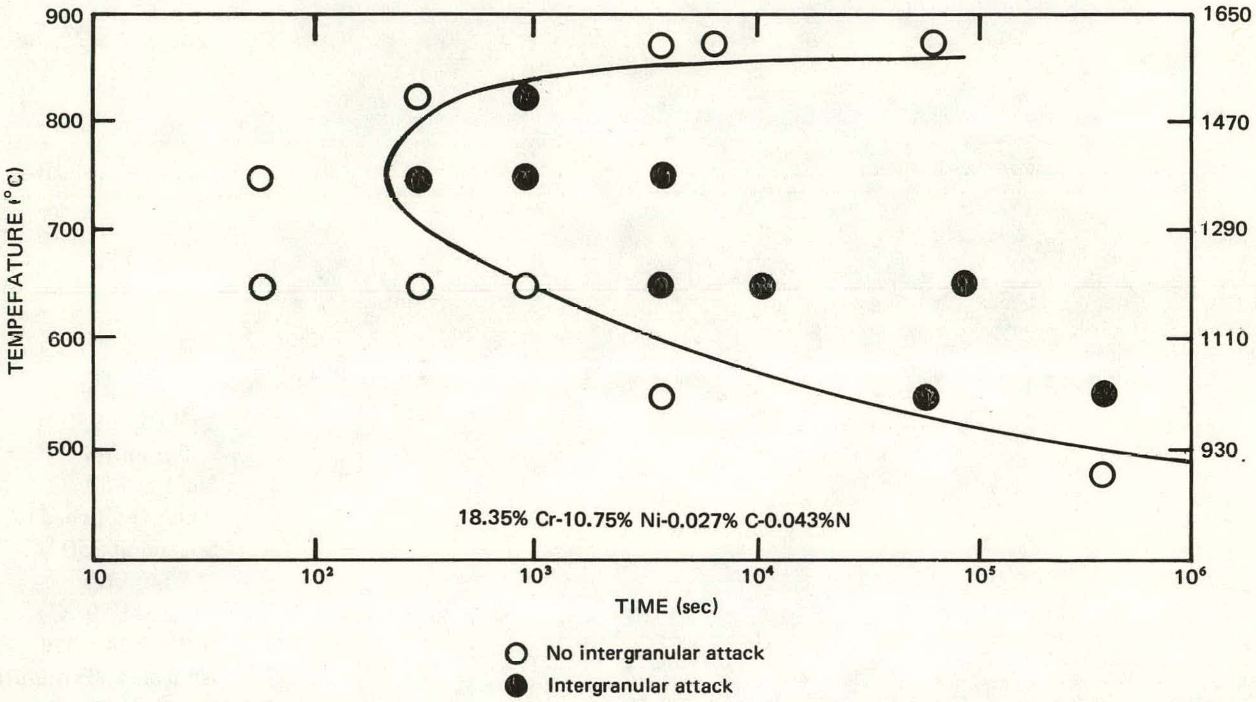


Specimen BA Hammer 1000X

Soaked at 950 °C
5 minutes
Hit 1 at 950 °C
Water Quenched
Soaked at 950 °C
5 minutes
Hit 2 at 950 °C
Water Quenched
Annealed 7½ minutes

Specimen JA Dynapak 1000X

9-12



*W. O. Binder et al., "Resistance to Sensitization of Austenitic Chromium-Nickel Steels of 0.03% Max. Carbon Content," *Transactions of the A.S.M.*, Vol. 41, p. 1322, (1949).

FIGURE 10. Time-Temperature-Precipitation Curve for a Type 304L Steel*