NASA-CR-172450

NASA Contractor Report 172450

NASA-CR-172450
19850023864

MACHINING - INDUCED DEFORMATION
IN STEPPED SPECIMENS OF
PH 13-8 Mo, 18 NICKEL MARAGING
STEEL GRADE 200T1 AND
GRAIN-REFINED HP 9-4-20

D. A. Wigley

Kentron International, Inc.
Hampton Technical Center
Hampton, VA 23666

Cryo Support Services, Inc. (Subcontractor)
New Castle, DE 19720

Contract NAS1-16000
June 1985

NASA
National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

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49      1      1 RN/NASA-CR-172450
            DISPLAY 49/2/1
        85N32177*#   ISSUE 21   PAGE 3565   CATEGORY 26   RPT#: NASA-CR-172450 NAS
        1.26:172450   CNT#: NAS1-16000   85/06/00  34 PAGES   UNCLASSIFIED
        DOCUMENT
  UTTL: Machining-induced deformation in stepped specimens of PH 13-8 Mo, 18
        nickel maraging steel grade 200T1 and grain-refined HP 9-4-20
  AUTH: A/WIGLEY, D. A.
  CORP: Kentron International, Inc., Hampton, Va.;  Cryo Support Services, Inc.,
        New Castle, Del.     AVAIL.NTIS   SAP: HC A03/MF A01
  COI:  UNITED STATES Prepared in cooperation with Cryo Support Services, Inc.,
        New Castle, Del.
  MAJS: /*DEFORMATION/*MACHINING/*MARAGING STEELS/*STAINLESS STEELS/*STRESSES/*
        WIND TUNNEL MODELS
  MINS: / CRYOGENIC WIND TUNNELS/ DIMENSIONAL STABILITY/ NICKEL ALLOYS/ STRESS
        CYCLES/ TOLERANCES (MECHANICS)
  ABA:  Author
  ABS:  The results of a study to evaluate the dimensional changes created during
        machining and subsequent cycling to cryogenic temperatures for three
        different metallic alloys are presented. Experimental techniques are
        described and results presented for 18 Ni Grade 200 maraging steel,
        PH-13-8 Mo stainless steel, and Grain-refined HP 9-4-20.

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Table of Contents

MACHINING-INDUCED DEFORMATION IN STEPPED SPECIMENS OF PH13-8MO, 18 NICKEL MARAGING STEEL GRADE 200TI. AND GRAIN-REFINED HP 9-4-20.

1. Introduction

1.1 Background

Dimensional instability in models intended for use in cryogenic wind tunnels is of serious concern and a program of work has been initiated at NASA LaRC to study its basic nature. As part of this program a simple stepped specimen configuration has been utilized as a basis for measuring dimensional changes created during machining and subsequent cycling between room and cryogenic temperatures. Results of the initial proof-of-concept tests on an 18 nickel 200 grade maraging steel specimen are given in references 1 and 2. The results of a further 17 specimens are given in ref. 3. A proposal for the use of stepped specimens in a systematic study of the dimensional stability of metallic alloys of interest for the fabrication of cryogenic wind tunnel models has been presented in ref. 4.

1.2 The Current Phase of Work

A critical evaluation of the results obtained from the initial work carried out on 18 nickel, 200 grade maraging steel, A286 and PH 13-8MO led to the decision to lengthen the unmachined 0.472 in. (12mm) thick section of the sample from 0.472 to 2.835 inches (12 to 72mm). The main reasons for this decision were to simplify leveling of the reference surface before validation, to improve reproducibility and to make the displayed results more meaningful. Three materials were chosen for evaluation in the current phase of work. They were put through a more elaborate sequence of machining, validation, heat-treatment and cryocycle stages. The materials chosen were; 18 Nickel Grade 200Ti. maraging steel, PH13-8Mo. and grain-refined HP 9-4-20.

1.2.1. 18 Nickel Grade 200Ti. Maraging Steel

The potential decline in availability and increase in price of cobalt have prompted one of the principal manufacturers of maraging steel to introduce a new, cobalt-free grade in which the precipitation hardening is due to the addition of titanium. A 250 grade, 250Ti, is already available commercially, and small quantities of a lower strength, higher toughness 200Ti grade have been produced for evaluation by NASA LaRC for potential use in the fabrication of models for cryogenic wind tunnels.

1.2.2. PH13-8MO

The earlier work on this material cast doubt on its dimensional stability after cryocycling, but problems encountered with leveling the specimens in a reproducible manner prevented an accurate assessment. A new configuration stepped specimen of PH13-8MO was therefore added to this phase of work.

1.2.3. Grain-Refined HP 9-4-20

In its regular form, the toughness of HP 9-4-20 is too low for it to be of use for constructing cryogenic wind tunnel models. Reduction in grain size is a classical technique for increasing the toughness of metallic alloys. A program to enhance the toughness of a number of alloys of interest for model construction has been under way at NASA LaRC for the last few years. The availability of a reasonable quantity of grain-refined HP 9-4-20 led to its choice for inclusion in this phase of the stepped specimen program.

2. Experimental Techniques

2.1 Machining Details

2.1.1 Support Fixture

Support of specimens during machining was by the use of a magnetic hold-down block for the initial maraging steel specimen described in ref. 2. The subsequent 17 specimens described in ref. 3. were held by clamping their sides. Neither method was considered to be adequately representative of the restraints likely to be experienced by a 2 or 3D wing while it was being machined. Therefore a new support fixture was designed for the new, larger stepped specimens that would more accurately simulate these restraints. This fixture is shown in Figure 1. A block of 416 stainless steel, size 8 x 5 x 0.75 in., forms the base plate to which an end restraint, size 2.5 x 0,75 x 0.75 in. is bolted. Three through-holes, made with a #7 (.2010 dia) drill are placed in the end restraint, one on the center line and one either side at 0.875 in. from the center line, and 0.236 in. above the surface of the base plate. The specimens are bolted rigidly to this end restraint so that their reference surface is held down onto the base plate.

Two side blocks fit one on each side of the specimen and have through holes centered at 3.300 in. from the end restraint and 0.236 in. above the surface of the base plate. Matching holes are located in the sides of the specimen and dowels are located through the side plates and into the specimen in order to hold the specimen down onto the base plate. A thin layer of grease or oil is placed between the specimen and base plate to keep swarf from getting under the specimen during machining.

2.1.2 Sequence of Machining and Validation Stages

As far as possible, all three specimens were to be put through the same machining schedule. Different grinding wheel and milling cutter speeds and feed rates per tooth were specified as appropriate for each material as detailed in Table 1. However, the initial rough machining stages on the HP 9-4-20 were carried out at slightly incorrect speeds. The original intent was to put all three specimens through the same machining and validation stages, with the addition of appropriate heat-treatment stages for the maraging steel and the PH13-8MO stainless steel. Large compressive stresses and upward deflections were, however, created during rough machining of the grain-refined HP 9-4-20 and it became necessary to carry out remedial work to reduce these stresses before proceding to the latter machining stages. Furthermore, an additional series of cryocycles were carried out at the end of the program to give a further check on the dimensional stability of these materials. The final schedule of machining and validating stages was as shown in Table 2.

The dimensions and shapes of the specimens after the various machining stages are shown in Figure 2.

2.2 Validation Procedures

Two different validation techniques had been used in the earlier phases of the stepped specimen program. For the proof-of-concept specimen, SOTON 1, continuous traces of Z deflection were plotted along three parallel lines from the thick root to the thin tip of the specimen, as well as transversely across its tip. The surface stresses can be calculated from the curvature of these traces if the beam thickness is known. In the subsequent work on 17 similar specimens, eight co-ordinate positions were specified along each of three parallel root-to-tip lines and Z deflections measured to give a total of 24 data points. A computer program was then written to plot out this data in the form of pseudo-isometric surfaces for each validation stage by joining together adjacent data points with straight lines.

As noted earlier, a larger specimen configuration was adopted for the current phase of work and six additional co-ordinates were defined for data gathering to give the 30 positions shown in Figure 3. The Z deflections at these co-ordinates for each validation stage of the three specimens are given in the Appendices, 1A through 1C.

2.2.1 The X-Y Table

In order to combine these two approaches to validating and displaying the specimen dimensions, as well as to minimize the amount of manual data reduction, a computer-controlled validation table was constructed. Data were to be taken at the 30 defined co-ordinate positions and enough intermediate positions to allow continuous traces to be plotted out and surface stresses to be calculated if required. The specimens were mounted in a fixture on top of one platten constrained to move in the X direction within an air bearing and driven by a computer-controlled stepper motor. This platten is supported by an air bearing on a second, larger platten constrained to move in the Y direction when driven by a second stepper motor. This larger metal platten is itself supported above an accurately flat granite block which acts as the base of the validator. Precalibration using optical flats showed that the specimen could be moved in the X-Y plane within an area of about 10 x 14 inches with deviations in the Z direction of a few 10's of microinches.

2.2.2 Z Measurement

Deflections of the specimen in the Z direction were measured using a contact-less capacitance probe with the output fed into a Wayne-Kerr bridge. The DC output signal from the bridge was digitized by an A/D converter and stored in the memory of a 32K desk-top computer in a 2D array, DF(I,J). Initially the maximum deflection capability was 0.010 in.(0.25 mm), but this was subsequently increased to 0.016 in.(0.4 mm) in order to cope with the large deflections created in the HP 9-4-20 specimen. The probe was calibrated using a jig with a large head micrometer and this also established the limits of the linear range of the probe. One possible drawback with the use of capacitance probes lies in their relatively large measuring area, about 0.080 in.(2 mm) in diameter, which evens out small variations in deflection. As, however, the reference surface of the stepped specimen has a lapped finish, and the changes in profile after machining are gradual, this is not a serious problem.

2.2.3 Measurement Sequence

The specimen was mounted on the validator with its reference surface facing upwards. The table was controlled manually to establish the unmachined end of the specimen as the Y=0 co-ordinate and the left hand edge as X=0. The specimen was then leveled by iterating around the three co-ordinate positions shown in Figure 3 as 1,5 and I, and adjusting the two leveling screws as appropriate. Given enough patience it would, in principle, be possible to level the specimen to better than about 50 microinches, but in practice 0.0001 in. was considered to be adequate. Once leveled, the specimen was moved so that the probe passed over a set of steps of known height so that its calibration could be checked.

The measurement sequence started at co-ordinate position 1 and deflections were measured at 0.040 in. (1 mm) intervals until position 2. At this point the measurement interval was reduced to 0.008 in.(0.2 mm). The deflections were then recorded up to co-ordinate position H and then stored in the results array at locations DF(1,6) to DF(1,354). The table then moved to position 3 and the second measurement sequence was carried out at the same intervals up to position P, with the results stored in locations DF(2,6) to DF(2,354). The final measurement sequence started at position 5, finished at X and the results were stored at locations DF(3,6) to DF(3,354). After measurement, the deflections at the three positions 1, 5 and I were rechecked. If they were not very similar to their original values the run was aborted and repeated. If satisfactory, the results array was stored on disk for subsequent analysis or plotting.

3. Presentation of Results

3.1 Graphical Representation

As noted earlier, the data from the 17 specimens described in Ref.3 was plotted to give a reasonable impression of the 3D shape of the reference surface after the various machining stages. In this early work the 8 data points on each line were joined with straight lines to give the impression of a continuous surface. In the current phase of the program, the availability of 348 data points per measurement sequence meant that the plotted curves were effectively continuous, as may be seen for example in Fig.4. It may also be seen that the 10 defined data positions on each line are marked with the appropriate identifying plot symbol, and that the three extreme data points are joined by straight lines to create the impression of the thin end of the specimen. The positions of the co-ordinates 1,2,A,----H; 3,4,I,---P; and 5,6,Q,---X correspond to the intersections of the straight lines marked on the reference surface of the specimen in each Figure. The appropriate data point is plotted above, or below, the co-ordinate position by an amount proportional to the measured deflection.

3.2 Accuracy and Reproducibility

The inherent stability of the air bearings supporting the plattens on the validator is such as to give a basic flatness to the X-Y measurement plane of about a few 10's of microinches Even occasional variations in the air supply pressure did not create errors in excess of 0.0001 in. in the Z deflection. As noted earlier it is possible to level the unmachined portion of the reference surface at positions 1,5 and I to better than 0.0001 in.. The thickness of the lines plotted in the figures is about 0.3 mm (0.012 in.), which corresponds to a deflection of about 50 microns on the scale used in the figures. In the majority of the figures it can be seen that the three separate plots are separated by no more than about two line widths in the unmachined region of the specimen. This indicates that the reproducibility between measurements is about 0.0001 to 0.00015 in.. It should be remembered, however, that there is a leverage effect because the three leveling points are at the thicker end of the specimen and this will approximately double the error at its tip.

4. Results for 18 Nickel Grade 200Ti. Maraging Steel

4.1 Validation Stages 2, 3 and 4

Three plots corresponding to validation stages 2,3 and 4 are shown in Fig. 4, labeled to indicate the appropriate machining stages. It can be seen that the deflections produced by milling the 0.035in. (6 mm) and 0.118 in. (3 mm) steps are both positive, indicating the presence of compressive stresses in the machined surfaces. Furthermore, the deflection after milling the 3mm step is approximately double that created by milling the 6mm step. This indicates that the magnitude of the surface stress is similar after both milling stages, as for a given stress level the deflection is inversely proportional to the beam thickness. The surface corresponding to the profile after the maraging heat-treatment can be seen to lie very close to that before heat-treatment. This confirms the excellent thermal dimensional stability of the 18 nickel maraging steels.

4.2 Validation Stages 4, 5 and 6

The profile after validation stage 4 is repeated in Fig. 5 to allow easy comparison with the two subsequent stages. The deflection after milling the 0.075in. (1.88 mm) step is so large that one extreme tip lies outside the range of the plotter and its magnitude, 0.013in. (0.325 mm), is greater than that found for previous maraging steel specimens. The subsequent grinding stage that reduces the thickness of the last 0.805in. (24mm) of the specimen to 0.060in. (1.50mm) induces tensile surface stresses. This both reduces the magnitude of the tip deflection and changes the direction of curvature of the last 24 mm.. Similar effects had been observed with previous specimens, the degree to which the grinding stage can modify the stresses induced by the previous milling stage being dependent on their relative magnitudes.

4.3 Validation Stages 6, 7 and 8

The profile shown in Fig. 6 by validation stage 7 appears to depart from that for the previous stage, 6,after the 4th plot symbol in each measurement sequence. This is perhaps a little surprising as only the last 0.472in. (12mm) of the specimen was machined in this stage. In other respects, however, the behavior is as expected in that the induced compressive surface stresses increase the positive deflection of the specimen tip. The final grinding stage which reduces the thickness of the last 0.472in. (12mm) to 0.030in. (0.75mm) reintroduces surface tensile stresses and reduces the tip deflection accordingly. Comparison of the curves for validation stages 7 and 8 shows that the effect of grinding is indeed limited to about the last 12mm of the specimen.

4.4 Validation Stages 8, 9 and 9X

The final operations carried out on this specimen consisted of three cryocycles from room to liquid nitrogen temperatures, accomplished by submerging the specimen in liquid nitrogen. The effect can be judged by comparing the profiles shown in Fig. 7 for validation stages 8 and 9, and this shows that the tip deflection increased by about 0.0005in. (0.02mm) after cryocycling. It may also be noticed that the plotted line starts to curve upwards after the first four plot symbols, as it had done for the earlier validation stages up to number 6. Although not in the original work plan, it was decided to carry out three further cryocycles to check the stability of the material. The results are indicated by the third profile labeled

9X. It can be seen that there is essentially no significant difference between the two profiles and thus the material has stabilized.

5. Results for PH13-8MO Stainless Steel

5.1 Validation Stages 2, 3 and 4

The three profiles shown in Fig. 8 are similar to those found for the previous maraging steel specimen. The tip deflection almost doubles between the 6mm and 3mm step machining stages, thereby confirming that the surface stresses are similar. Heat-treatment does, however, create a considerably larger deflection with a sign that infers either increased compressive stresses in the machined surface and/or tensile stresses in the reference surface.

5.2 Validation Stages 4, 5 and 6

As may be seen from Fig. 9, the milling stage used to form the 0.075in. (1.88mm) step created larger compressive surface stresses than the two milling stages carried out before heat-treatment and the tip deflections were more than doubled. A subsequent grinding stage to reduce the thickness of the step to 0.060in. (1.50mm) decreased the magnitude of the tip deflection and changed the curvature to reflect the influence of the tensile surface stresses induced by grinding.

5.3 Validation Stages 6, 7 and 8

Milling the 0.40in. (1.00mm) step introduced further compressive stresses in the tip of the specimen. As may be seen by comparison of the profiles after validation stages 6 and 7 in Fig. 10, the two curves deviate after the third plot symbol from the end of the curves, indicating the localized extent of the stresses. The final grinding stage that reduced the thickness of the last 0.472in. (12mm) to 0.030in. (0.75mm) created tensile surface stresses. These stresses reduced the tip deflection and recovered about half the deflection induced by the previous milling stage.

5.4 Validation Stages 8, 9 and 9X

As may be seen from Fig. 11, the first series of three cryocycles reduced the deflection of the part of the specimen covered by the last four plot symbols compared to its position after the last grinding operation. The fact that the deflections were reduced infers either that the residual compressive stresses were lowered, or that compensating tensile stresses were induced, by cryocycling. This would appear to be the opposite effect from that found with the maraging steel where the tip deflections were increased during cryocycling. In order to investigate further the effect of cryocycling, an additional series of three cryocycles was performed with the results shown by validation stage 9X. It can be seen from the almost identical profiles of the specimen after the two series of cryocycles that the material had stabilized completely after the first three cryocycles.

6 Results for Grain-Refined HP 9-4-20

6.1 Validation Stages 2, 3 and 4

The deflections produced by milling the 0.235in. (6mm) thick step in the grain-refined HP 9-4-20 specimen were of a similar sign and magnitude to those set up in the previous maraging steel and PH13-8Mo specimens. It was therefore somewhat surprising that the deflection produced by milling the 0.118in (3mm) thick step was so much larger than those set up in the other two materials by the same machining operation. As noted earlier the cutter speed and feed rates were not optimized for milling HP 9-4-20 and this might be a cause of the extra induced stresses. However it is difficult to appreciate why the effect was not seen after milling the first step. As noted earlier the validator was modified to accommodate these larger-than-expected deflections. It was decided that a remedial heat-treatment should be attempted to reduce the deflections so that the rest of the machining stages could be completed without creating excessive deflections. It was, however, imperative that the temperature should be kept below that which would cause grain-growth and reduce the toughness of the material. After discussion with NASA engineers it was decided that 1 hour at 900F (482C) should be adequate and the specimen was heat-treated accordingly. Metallographic studies of the material before and after heat-treatment confirmed that no grain-growth had taken place. Comparison of the profiles shown in Fig.12 for validation stages 3 (before) and 4 (after) heat-treatment showed that some worthwhile recovery had indeed occurred.

6.2 Validation Stages 4, 4X and 4G

Encouraged by the recovery achieved by heat-treating for 1 hour at 900F, it was decided to carry out a second treatment at the same temperature for 2 hours to see whether any further recovery could be achieved. However, as may be seen from comparison of the profiles in Fig. 13 after the first heat-treatment, stage 4, and the second, stage 4X, there was little additional worthwhile recovery. Worse still, the profile of the unmachined part of the specimen became slightly curved, most probably due to the formation of oxide on the reference surface. This meant that subsequent validation stages were not strictly comparable to the previous stages. Furthermore the deflection was still larger than that thought desirable and it was therefore decided to grind a thin layer off the surface to induce tensile stresses that would partially compensate for the residual compressive stresses in the specimen. The results are shown in Fig. 13 by profile 4G and it may be observed that the deflections are indeed reduced to the same magnitude as those created by milling the 0.118in. (3mm) step in the other two materials.

6.3 Validation Stages 5, 6 and 7

The usual sequence of machining operations was recommenced by milling the 0.075in. (1.88mm) step on the end of the specimen. As may be seen from the profile labeled number 5 in Fig. 14, the deflection increased to a value similar to that found in the PH13-8MO specimen at the same stage. Grinding the same step down to a thickness of 0.060in. (1.50mm) induced surface tensile stresses which partially offset the residual compressive stresses and approximately halved the tip deflection. The final profile shows that milling the 0.400in. (1.00mm) step virtually restored the tip deflection to the same value as it had after the previous milling stage.

6.4 Validation Stages 8, 9 and 9X

Grinding the final 0.030in. (0.75mm) thick step created the profile given by validation stage 8 in Fig. 15, inferring some reduction in the compressive stresses induced by milling. The profile after three cryocycles lies above that left after grinding, suggesting either that the tensile stresses had been reduced or that compressive stresses had been increased as a result of cryocycling. This movement was in the same sign, but of a larger magnitude, as that found in the maraging steel and of the opposite sign to the PH13-8MO. A second set of cryocycles was then carried out and validation stage 9X shows the resultant profile. Problems arose with the validator about two thirds of the way through and only the first two linear profiles, 1-H and 3-P are reliable. These would appear to show that the material was still moving, but in the opposite direction to that shown by the first series of cryocycles. Further work would be necessary to clarify this point should the material be deemed worthy of further effort.

7 Discussion

The results obtained from these three stepped specimens have confirmed and clarified a number of the effects shown in the fist two phases of the program and extended the study to cover two additional materials. The computer-controlled, air bearing supported validator has been shown capable of giving results of significantly higher accuracy and reproducibility than those obtained in the earlier phases. Detailed comparison with the results of the earlier work on maraging steel is not always possible because of changes and additions to the machining and validation sequences utilized. However some conclusions can be drawn:

7.1 18 Nickel Grade 200 Ti. Maraging Steel

There do not appear to be any major differences between the behavior of the new and the old 200 grades of maraging steel that could not be accounted for by differences in the supporting fixtures and machining operation procedures. Perhaps the only significant point to note in this context is the relatively large deflection produced by milling the 0.075in. (1.88mm) step after heat-treatment. This was almost twice as large as that in the first specimen, SOTON 1. The relevance, or otherwise, of this observation will only become really apparent when a specimen of regular 18 nickel 200 grade maraging steel having the larger configuration is put through an identical series of machining and validation stages. The other significant point concerns the stability of the material, both after the maragining heat-treatment and after cryocycling, which is at least as good as in the regular cobalt-bearing 200 grade material.

7.2 PH13-8MO Stainless Steel

Detailed comparison with the earlier work is made difficult by the poor quality reference surfaces on the earlier specimens. However, in general the two sets of results are similar, both in sign and magnitude. The decrease in deflection between milling the 0.075in (1.88mm) thick step in stage 5, and the subsequent grinding stage 6 in which the thickness is reduced to 0.060in. (1.50mm), is significantly smaller in the newer specimens. This probably reflects the changes made in the support fixture and/or greater care with the grinding operation which resulted in the generation of lower tensile surface stresses. A further, welcome, result concerns the stability after cryocycling, which was in some doubt after the earlier work. The current work confirms that PH13-8MO does indeed undergo small dimensional changes after the first three cryocycles, but that there is no further movement after the second series. Thus, in practice, cryocycling during and after the final machining stages of a models construction should stabilize the material and prevent further dimensional instability in service.

7.3 Grain-Refined HP 9-4-20

The very large deflections set up while milling the 0.235in. (3mm) thick step in this material are of serious concern, even after allowing for the fact that the cutter and feed speeds were not completely optimized. The experienced operator who carried out this work commented that it was one of the worst materials he had ever had to mill, but that it ground very freely. It will be of interest to see whether similar problems are encountered with the back-up specimens being machined at NASA LaRC. The apparent poor stability during cryocycling is also of concern and needs confirmation. Compared to the other two materials studied, the grain-refined HP 9-4-20 does not seem to be such a promising material for the construction of models for cryogenic wind tunnels.

8. Recommendations for Further Work

The report cited as ref. 4 is a comprehensive discussion of the way that the stepped specimen program could be extended to create the basis for the systematic, long term study of dimensional stability in those materials of interest for the construction of models for cryogenic wind tunnels. In the short term it is suggested that one material, probably 18 nickel maraging steel or A286, should be selected for an in-depth study. It is further suggested that the effects of milling and grinding should be examined using separate specimens and that annealing heat-treatments should be studied to see how machining-induced dimensional changes could be recovered.

9. References

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2. Wigley, D.A. "A Proposed Configuration for a Stepped Specimen to be used in the Systematic Evaluation of Factors Influencing Warpage". NASA CR 166004, August 1982.

3. Wigley, D.A. "The Dimensional Stability Analysis of Seventeen Stepped Specimens of 18 Nickel 200 Grade Maraging Steel, PH13-8MO and A-286". NASA CR 172168. August 1983.

4. Wigley, D.A.: "A Systematic Plan for the Continued Study of Dimensional Stability of Metallic Alloys Considered for the Fabrication of Cryogenic Wind Tunnel Models". NASA CR 172449, November, 1984.

TABLE 1 FABRICATION PARAMETERS USED IN PREPARING STEPPED SPECIMENS

PARAMETER \ MATERIAL	18 NICKEL 200Ti	PH13-8Mo		HP 9-4-20
MILLING				
CUTTER TYPE	High Speed Steel 1/2 in dia., 2 fluted ball-ended cutter			
CUTTER SPEED (ft/min)	60	* 60 (70)		* 60 (55)
FEED PER TOOTH (in)	.001	* .001 (.0007)		* .001 (.0005)
DEPTH OF CUT (in)	.02	.02		.02
COMMENTS	* incorrect rate (recommended rate) HP 9-4-20 very difficult to mill			
GRINDING				
WHEEL TYPE	WA46JV 7 x 1.25 x 0.5 in 2850 rpm			
WHEEL SPEED (ft/min)	* 5220 (4000)	* 5220 (5500)		* 5220 (4000)
TABLE SPEED (ft/min)	50	50		50
CROSS FEED (in)	.05	.025		.05
DOWN FEED, rough (in) " " , fine (in)	.003 .001	.001 .0005		.002 .0005
COMMENTS	* incorrect rate (recommended rate) HP 9-4-20 ground easily			
HEAT-TREATMENT				
TEMPERATURE (F) " [C]	925 [496]	a 1400 [760]	b 1150 [620]	900 [482]
TIME (hr)	4	2 +A.C.	4+ A.C.	1, then 2
COMMENTS	standard heat-treatment	two stage heat-treatment, A.C. = air cool		1st for 1 hr. 2nd for 2 hr. remedial h.t.

TABLE 2 FINAL SCHEDULE OF MACHINING AND VALIDATION STAGES

	OPERATION	VALIDATION STAGE
1	Ball mill slab to size and lap reference surface	V1
2	Ball mill 48mm (1.890in) long step to 6mm (.235in) thick	V2
3	Ball mill 36mm (1.417in) long step to 3mm (.118in) thick	V3
4	Heat-treatment as detailed in Table 1	V4
4X	2nd remedial heat-treatment for HP 9-4-20 only	V4X
4G	Remedial grinding stage for HP 9-4-20 only	V4G
5	Ball mill 24mm (.945in) long step to 1.88mm (.075in) thick	V5
6	Grind 20mm (.805in) long step to 1.50mm (.060in) thick	V6
7	Ball mill 12mm (.472in) long step to 1.00mm (.040in) thick	V7
8	Grind 10mm (.374in) long step to 0.75mm (.030in) thick	V8
9	3 Cryocycles by immersion into liquid nitrogen	V9
9X	Additional 3 cryocycles into liquid nitrogen	V9X

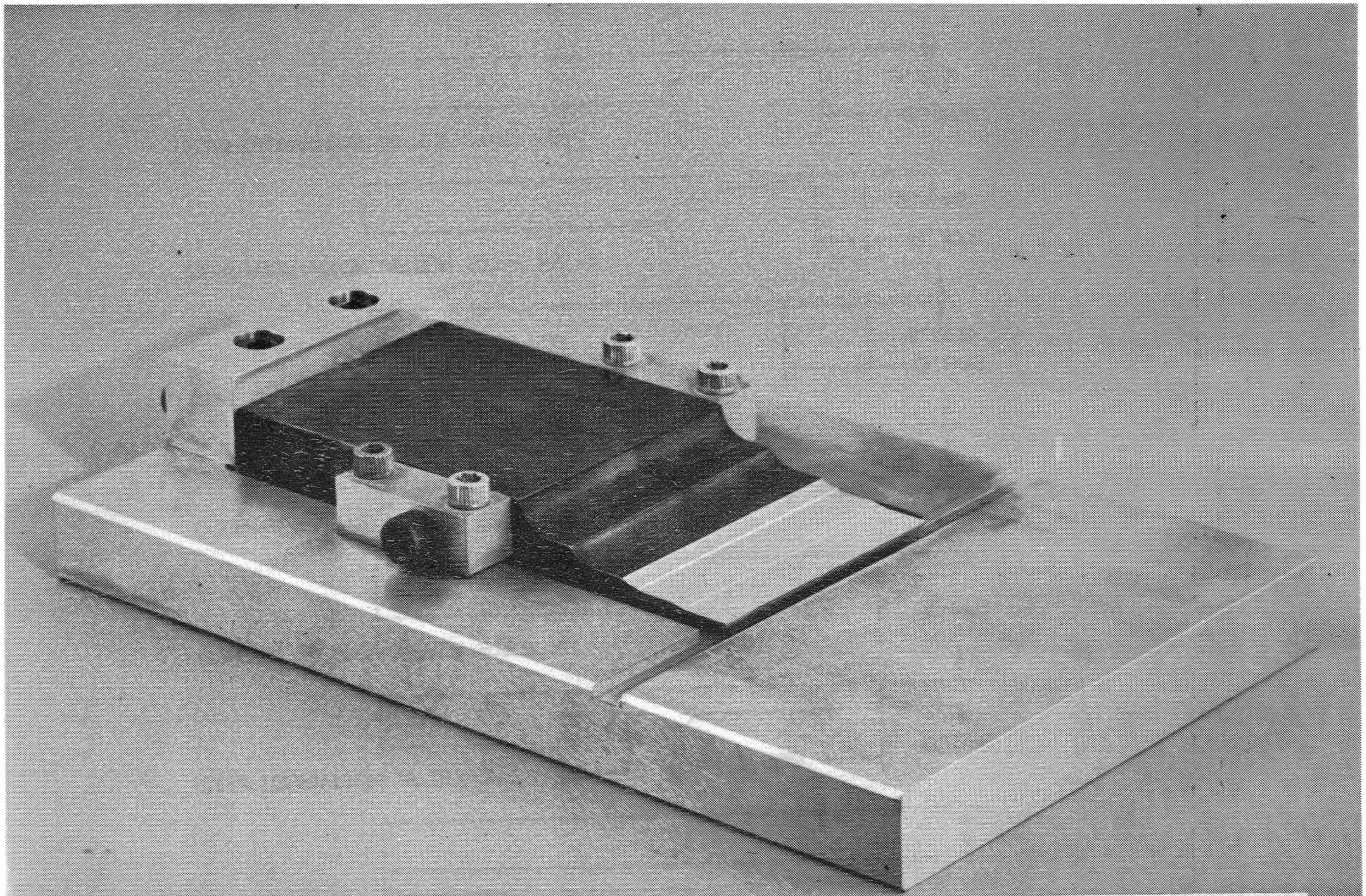


FIGURE 1 VIEW OF STEPPED SPECIMEN IN ITS MACHINING SUPPORT FIXTURE

All dimensions in inches.

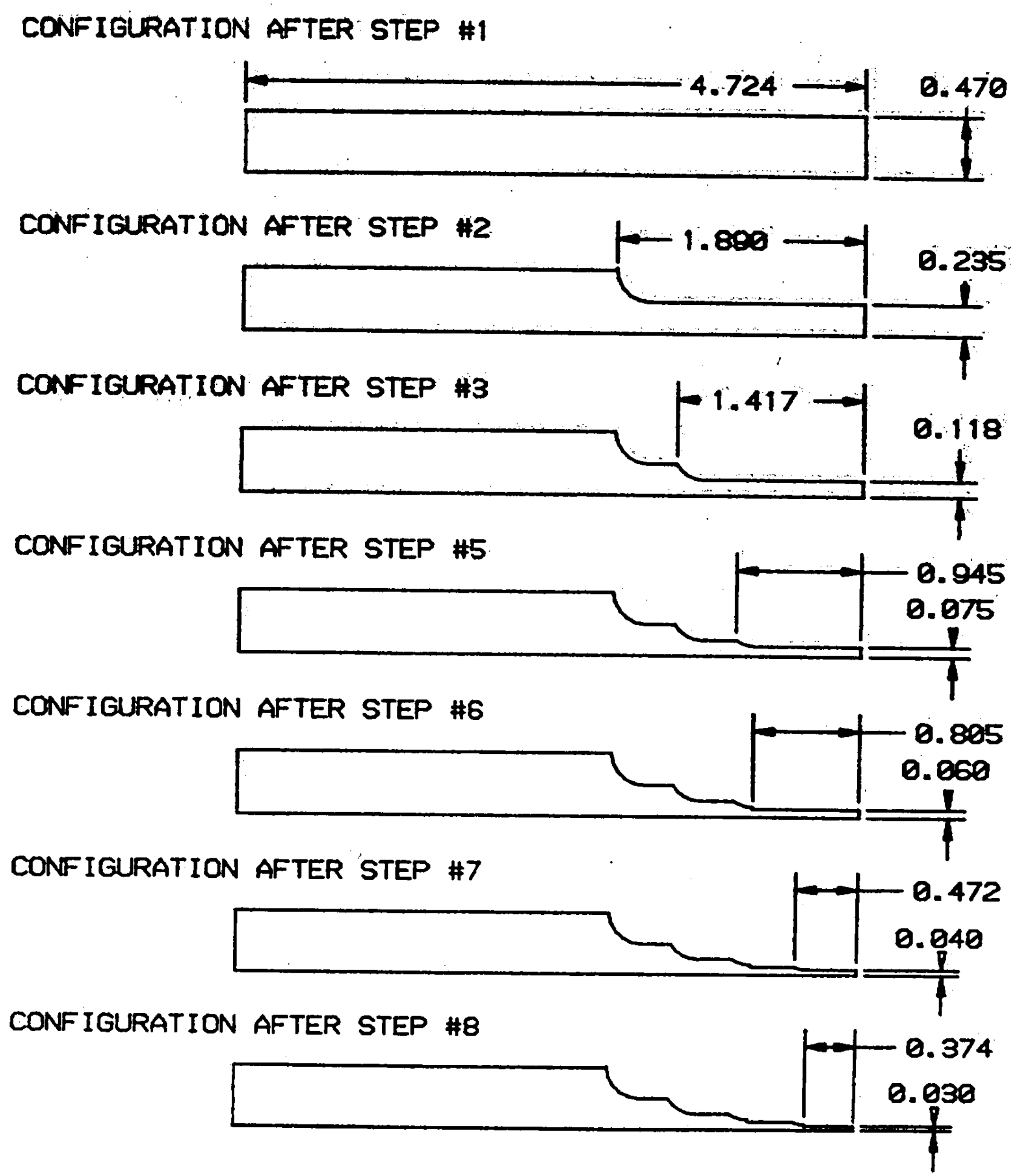


FIGURE 2 DIMENSIONS AND PROFILES OF STEPPED SPECIMENS AFTER INDICATED MACHINING STAGES

All dimensions in inches.

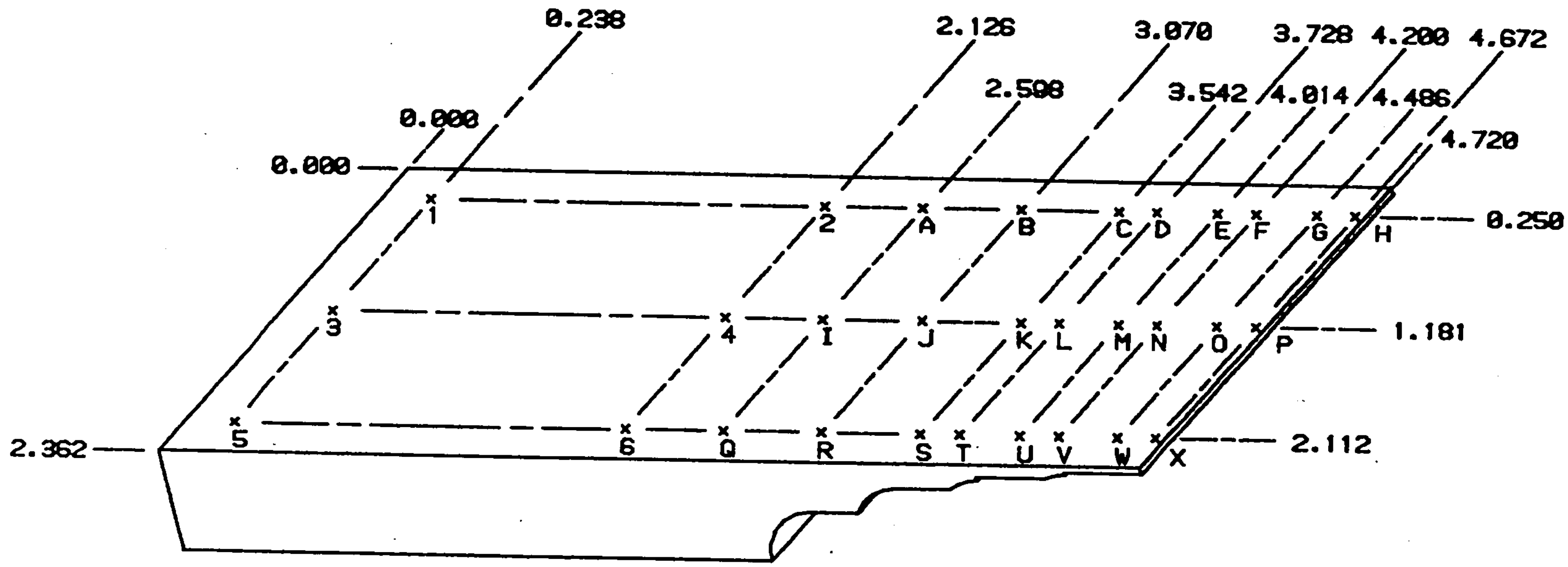
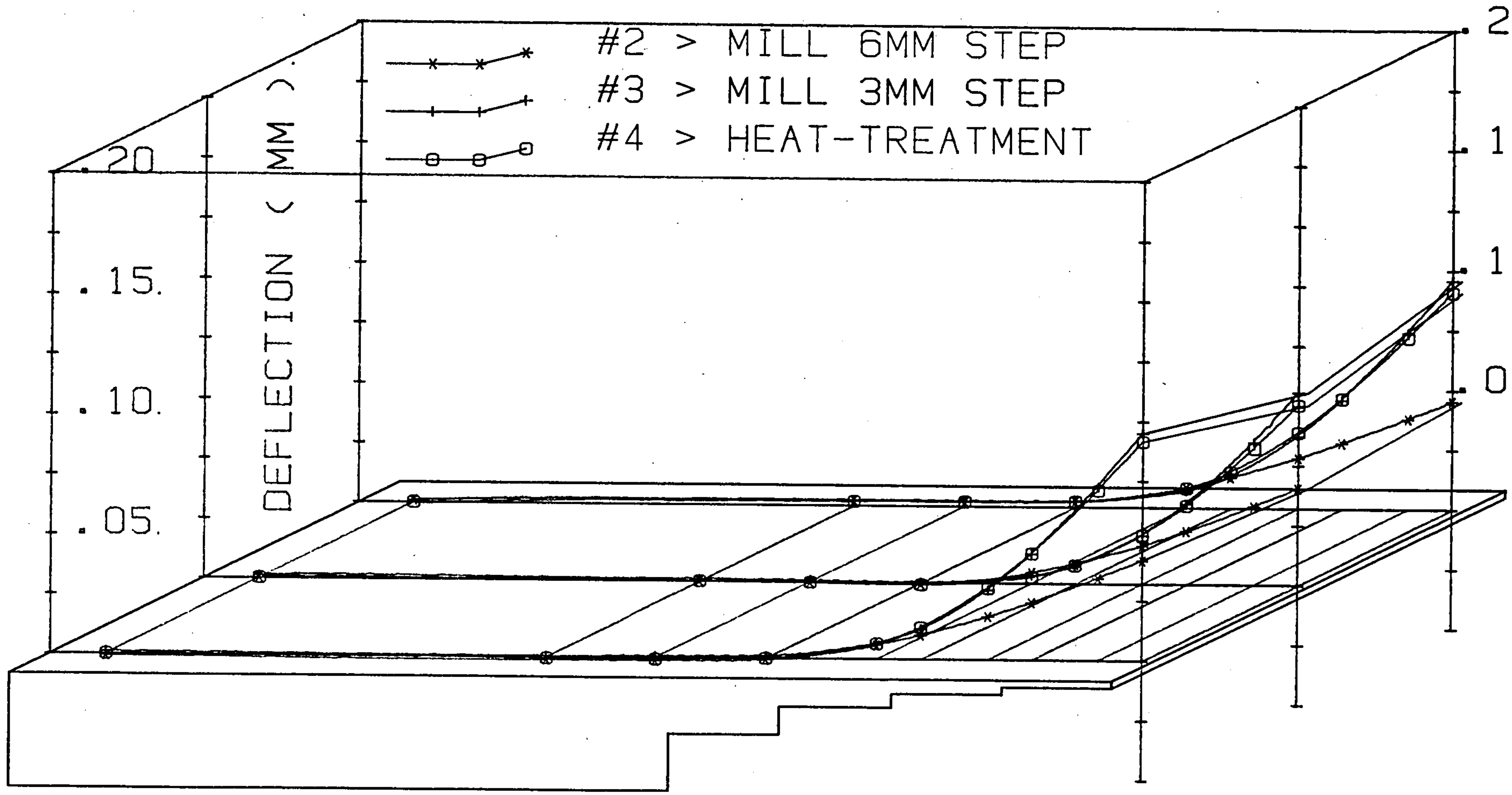
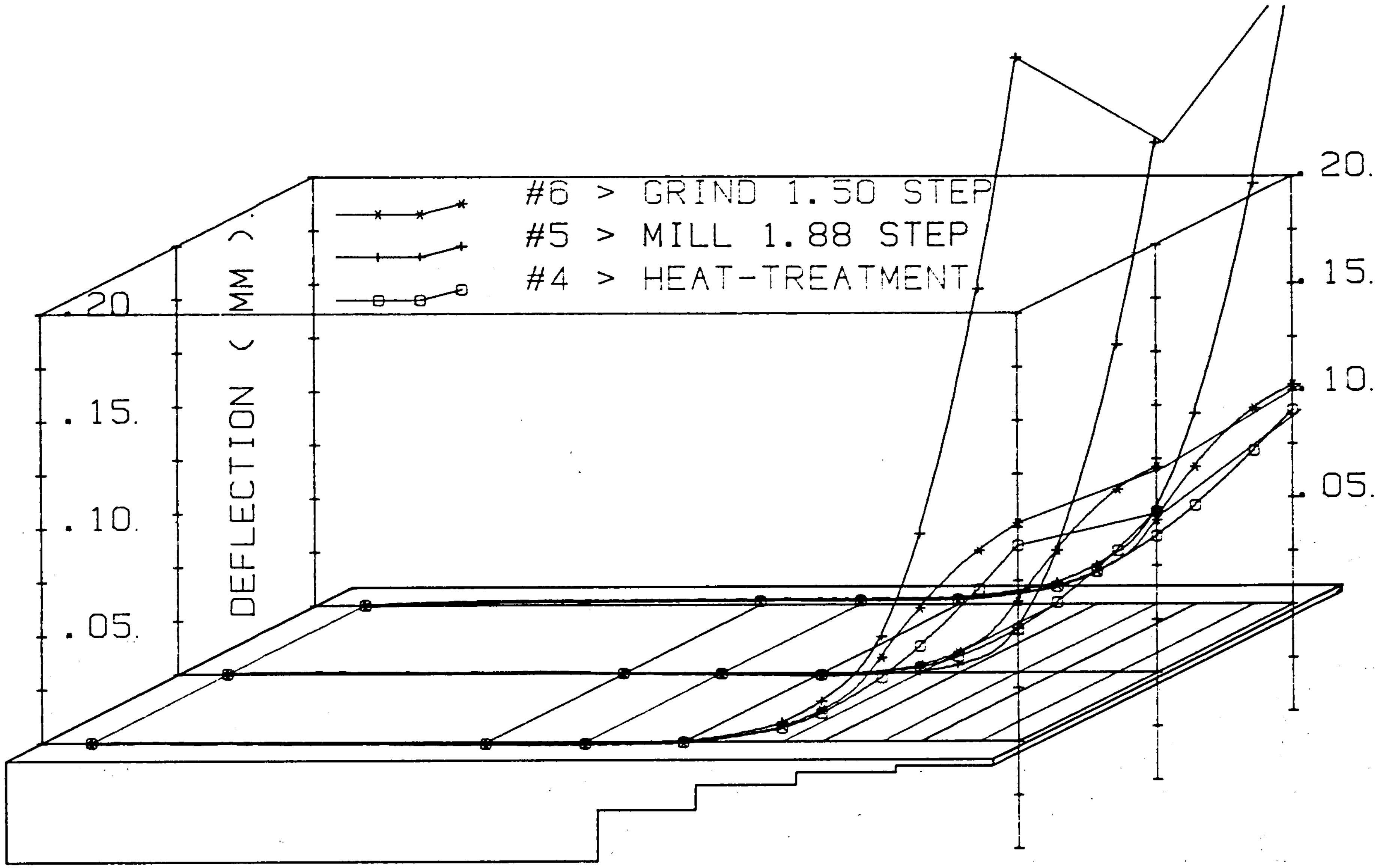


FIGURE 3 LOCATIONS OF THE 30 VALIDATION CO-ORDINATES ON THE REFERENCE SURFACE OF THE STEPPED SPECIMENS



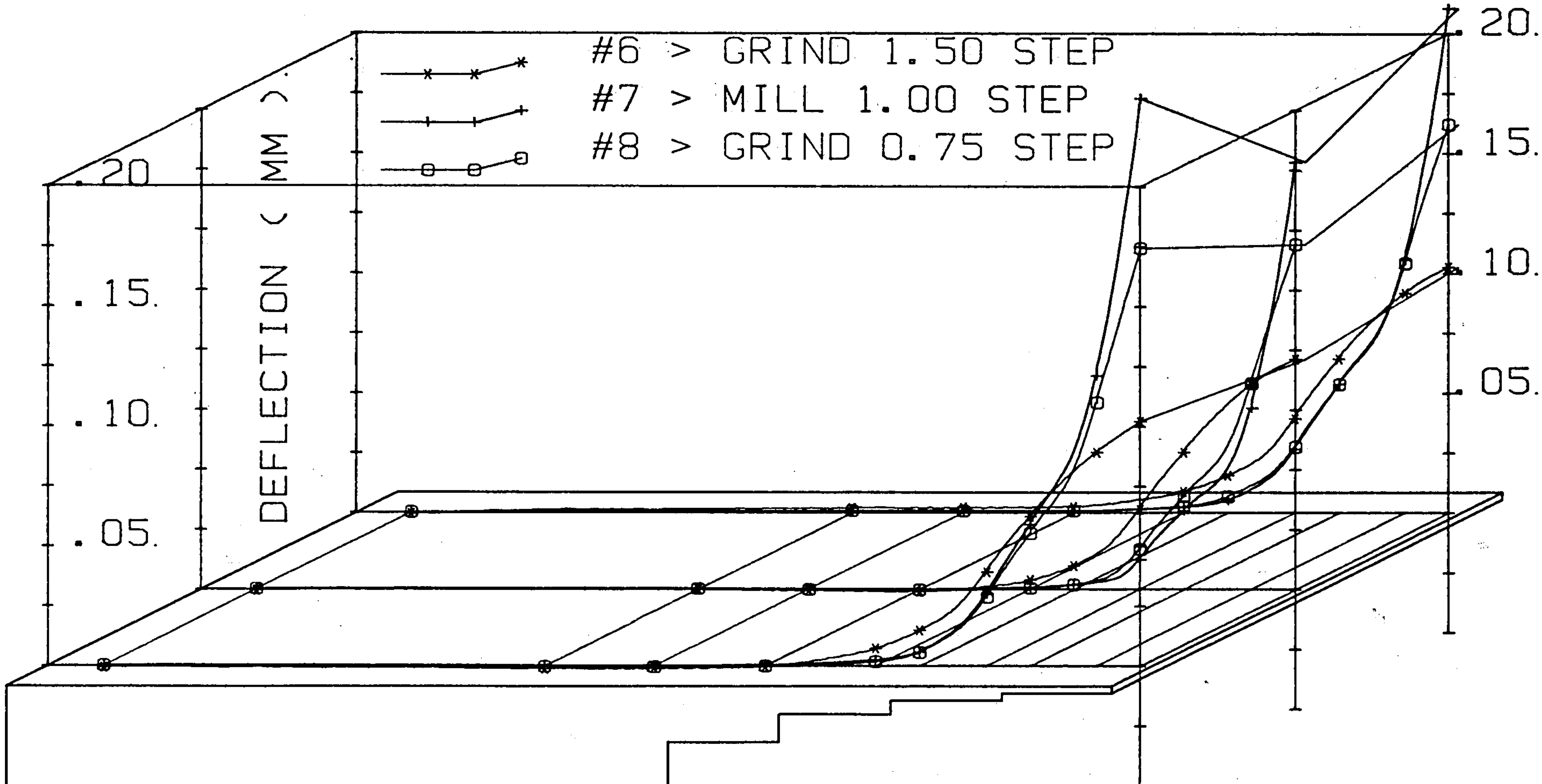
MATERIAL 18 NI GRADE 200T

FIGURE 4 RESULTS OF VALIDATION STAGES 2, 3 & 4



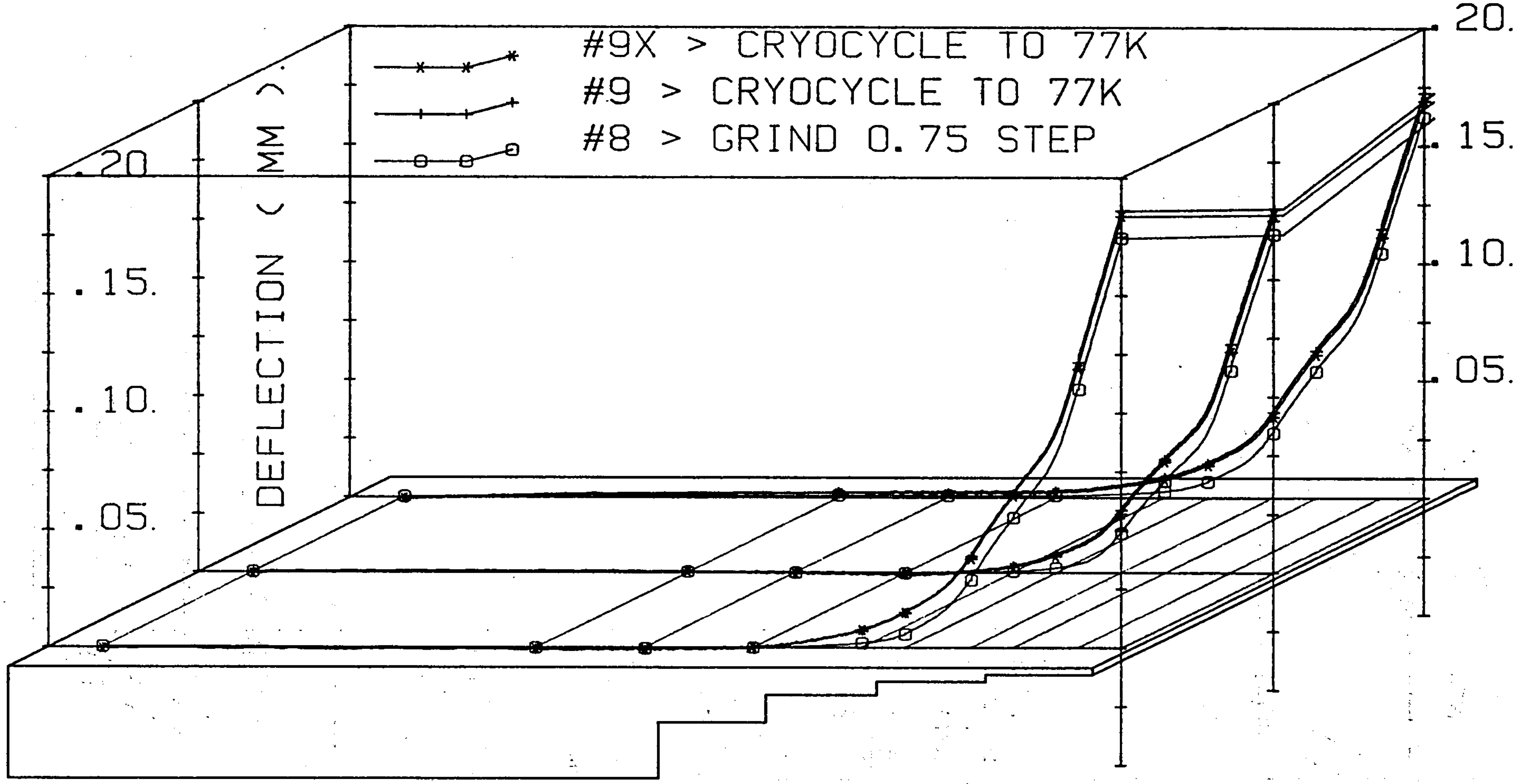
MATERIAL 18 NI GRADE 200T

FIGURE 5 RESULTS OF VALIDATION STAGES 4, 5 & 6



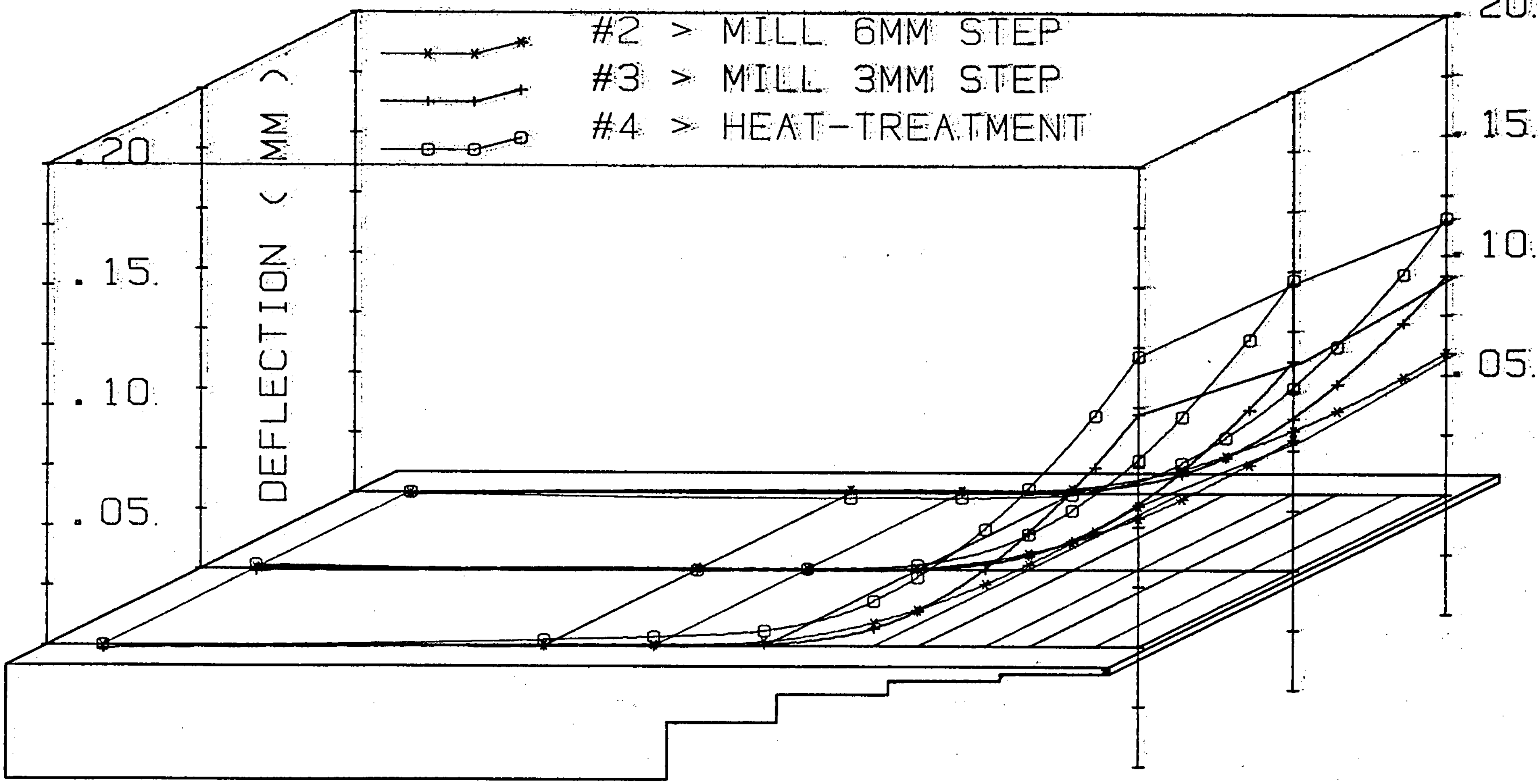
MATERIAL 18 NI GRADE 200T

FIGURE 6 RESULTS OF VALIDATION STAGES 6, 7 & 8



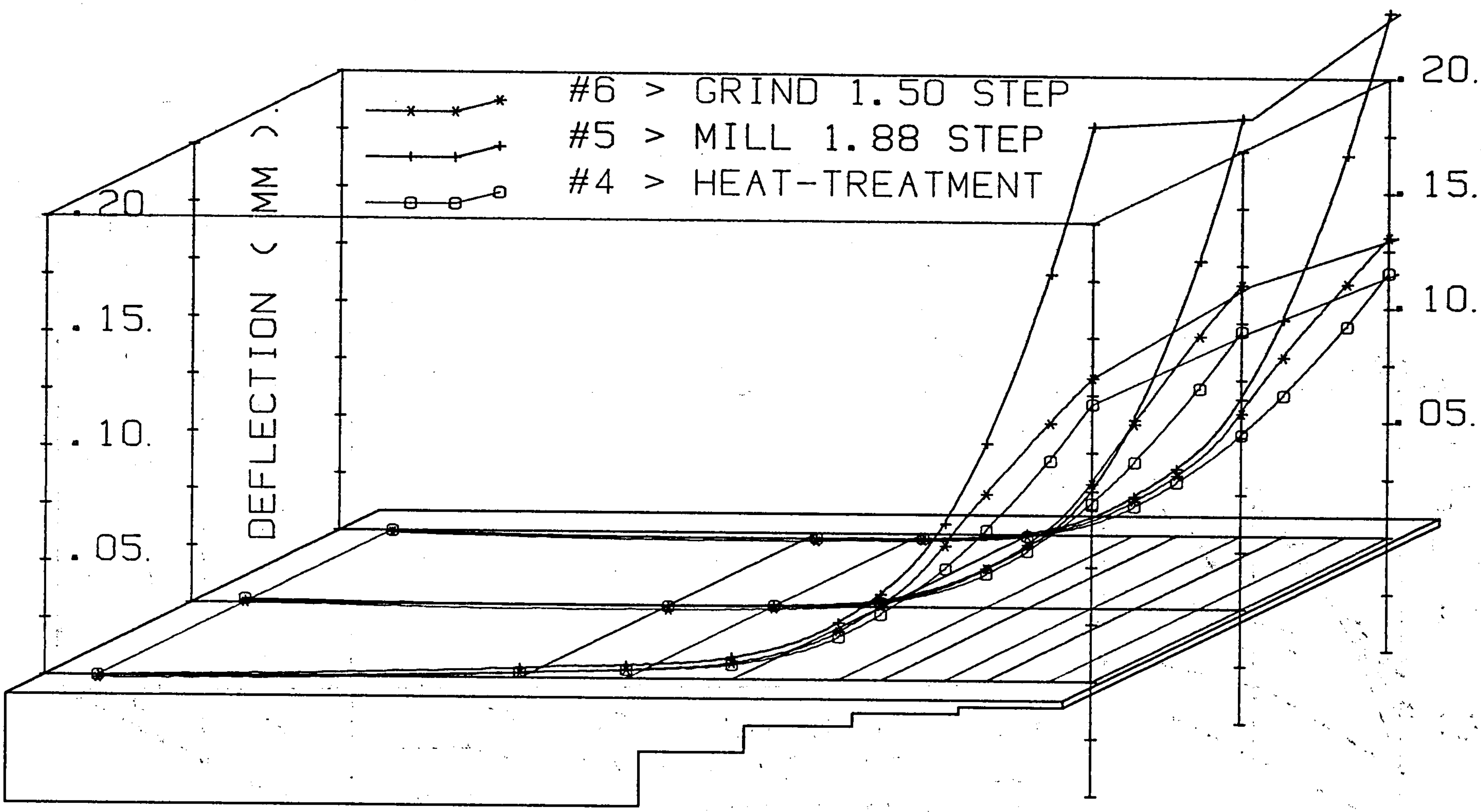
MATERIAL 18 NI GRADE 200T

FIGURE 7 RESULTS OF VALIDATION STAGES 8, 9 & 9X



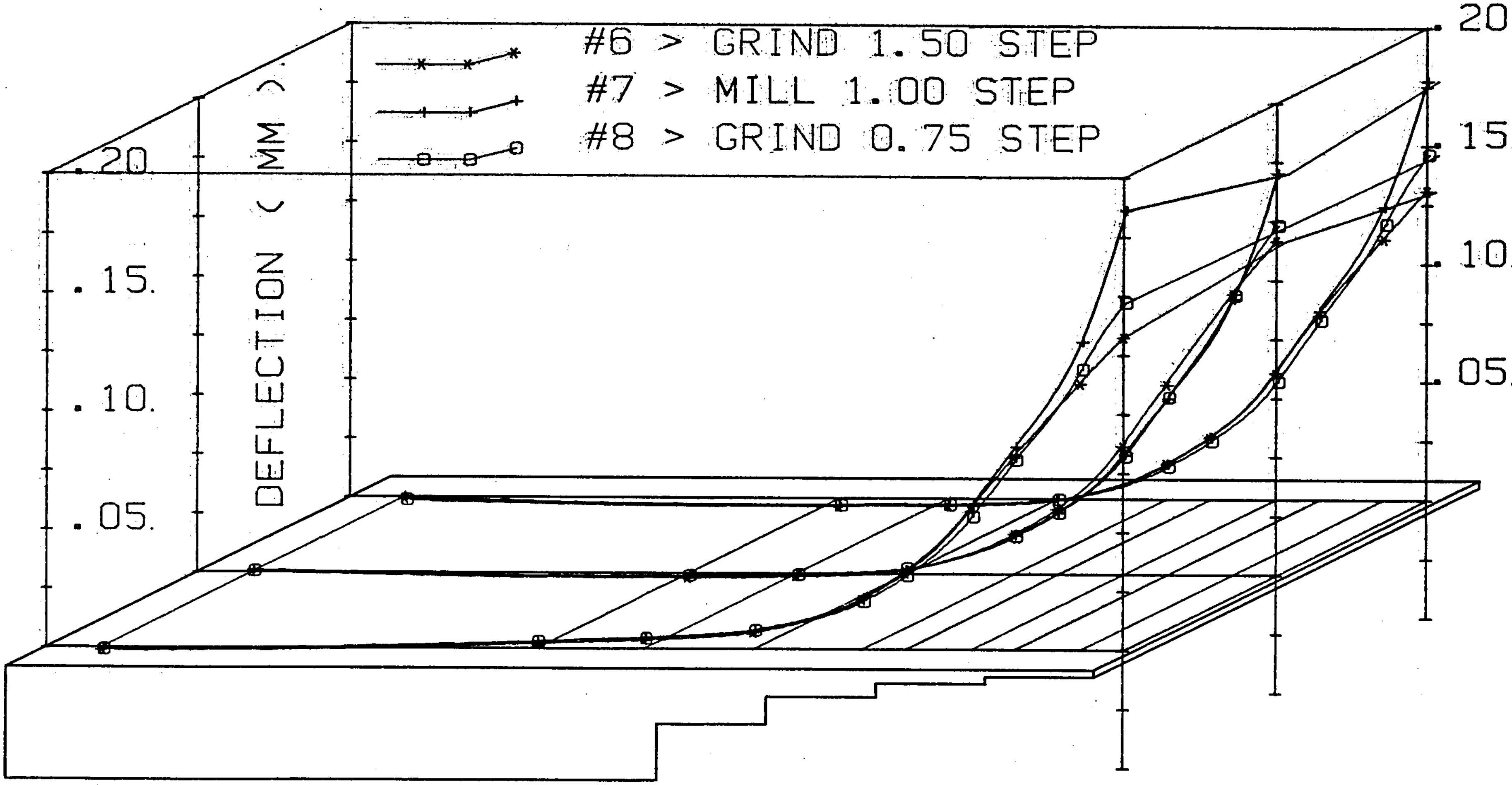
MATERIAL 13-8 MO

FIGURE 8 RESULTS OF VALIDATION STAGES 2, 3 & 4



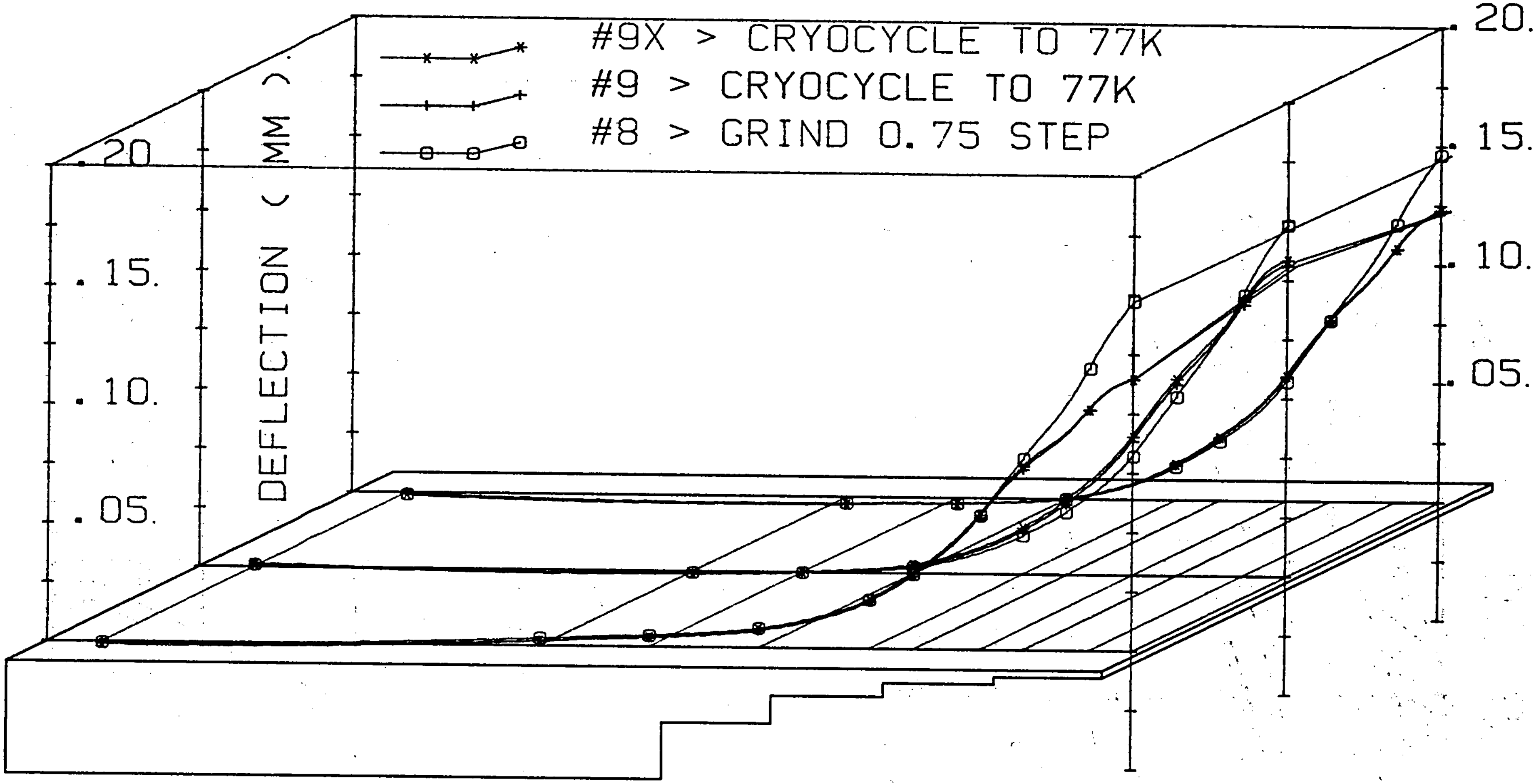
MATERIAL 13-8 MO

FIGURE 9 RESULTS OF VALIDATION STAGES 4, 5 & 6



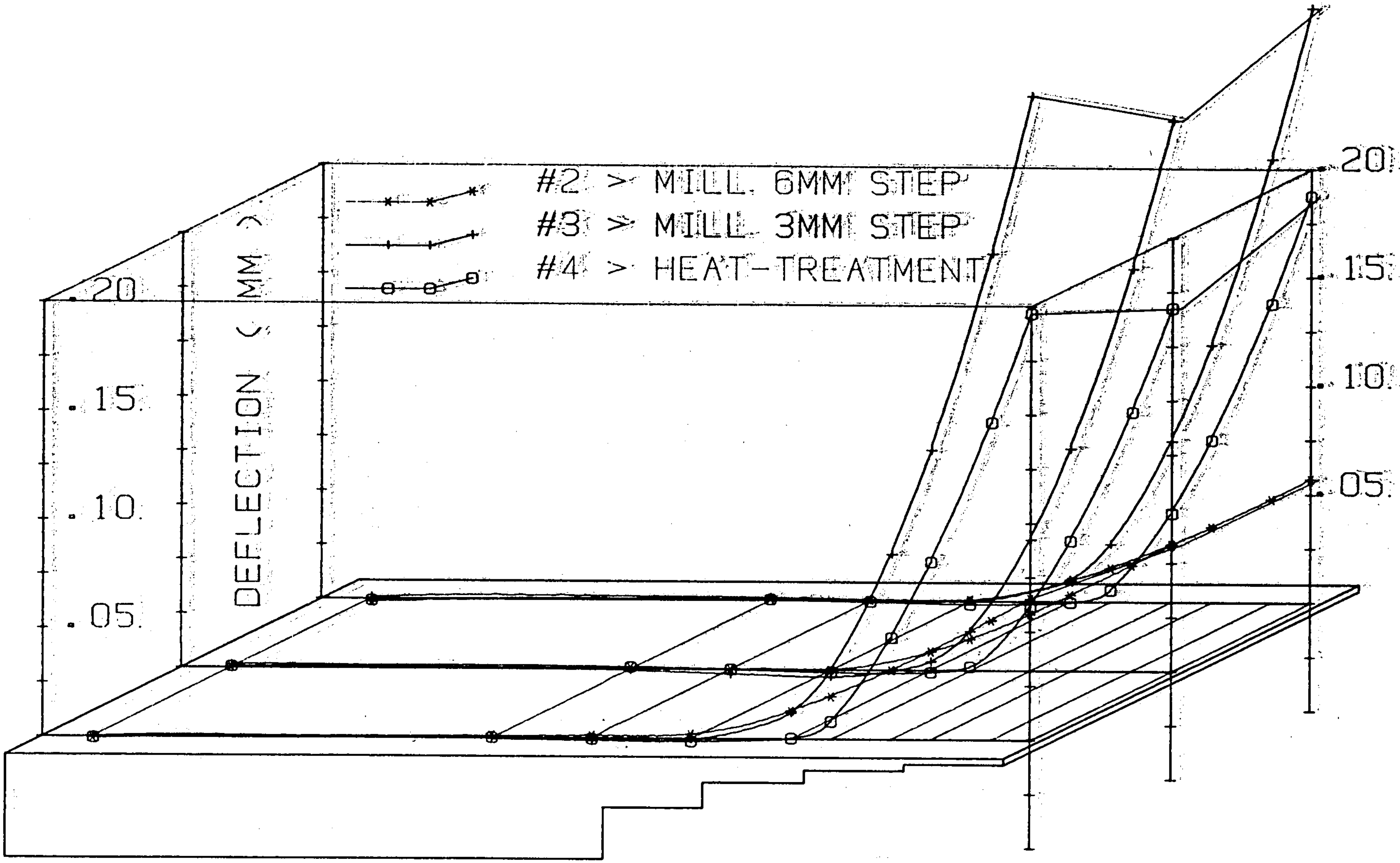
MATERIAL 13-8 MO

FIGURE 10 RESULTS OF VALIDATION STAGES 6, 7 & 8



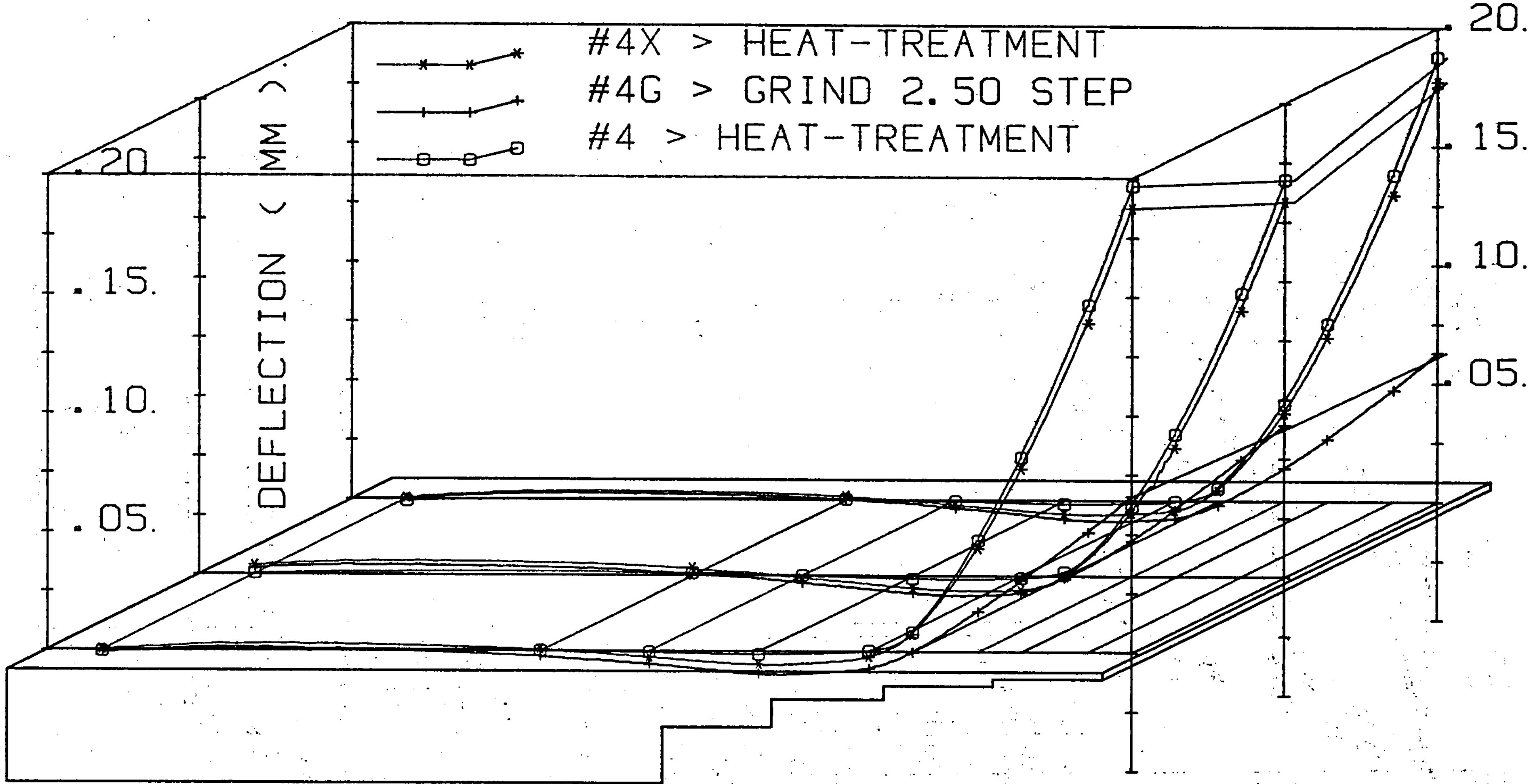
MATERIAL 13-8 MO

FIGURE 11 RESULTS OF VALIDATION STAGES 8, 9 & 9X



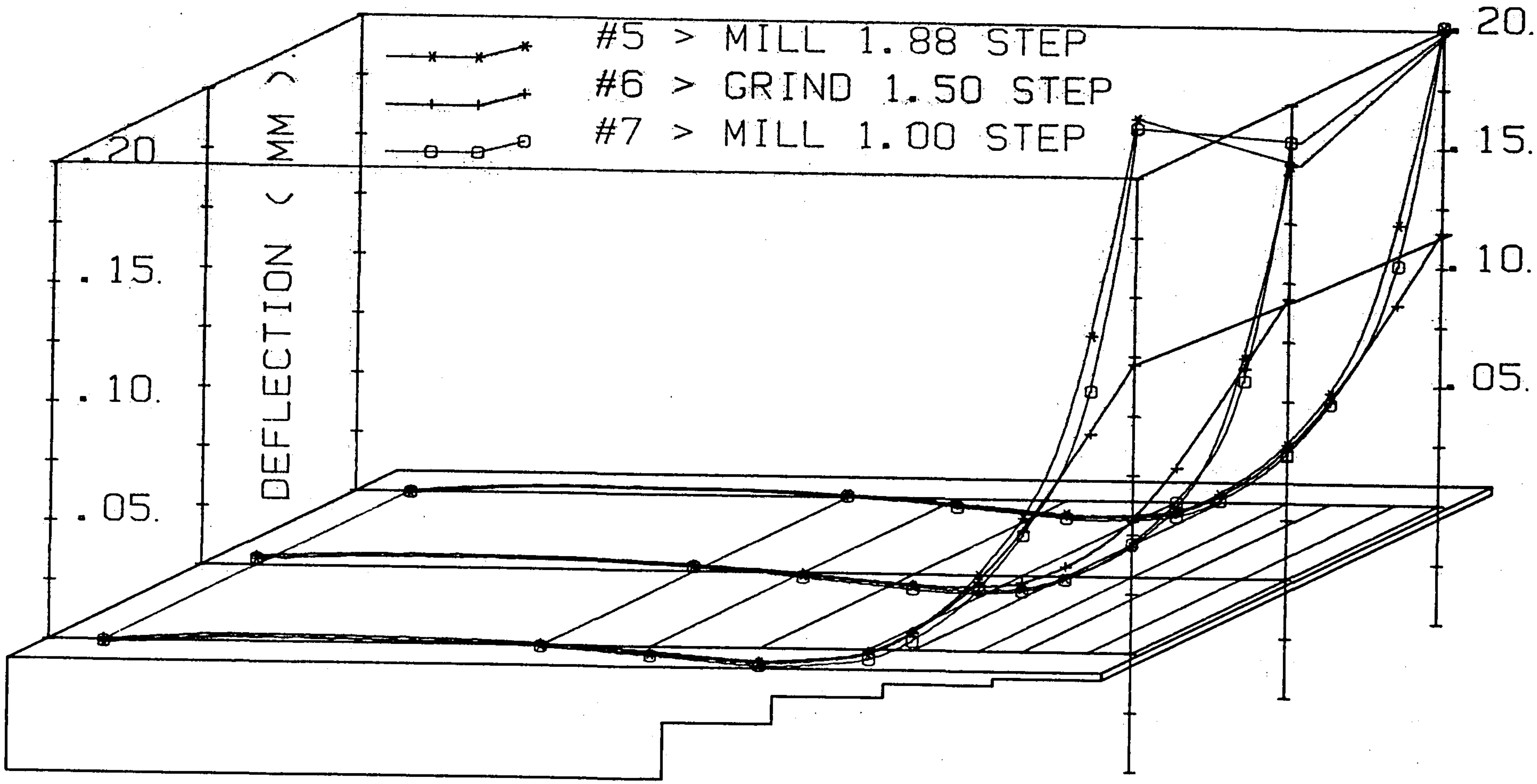
MATERIAL HP 9-4-20 SGR

FIGURE 12 RESULTS OF VALIDATION STAGES 2, 3 & 4



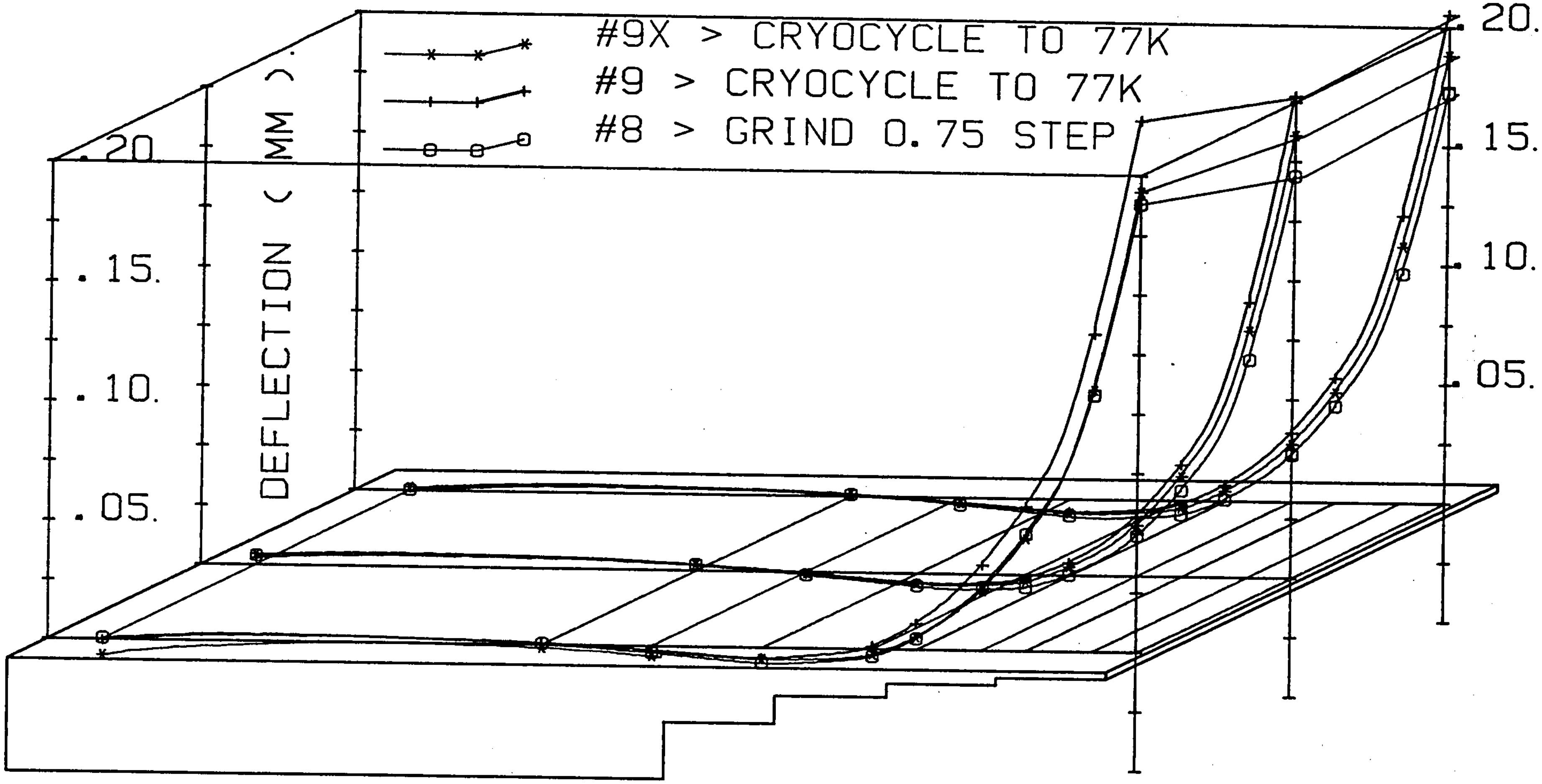
MATERIAL HP 9-4-20 SGR

FIGURE 13 RESULTS OF VALIDATION STAGES 4, 4X & 4G



MATERIAL HP 9-4-20 SGR

FIGURE 14 RESULTS OF VALIDATION STAGES 5, 6 & 7



MATERIAL HP 9-4-20 SGR

FIGURE 15 RESULTS OF VALIDATION STAGES 8, 9 & 9X

APPENDIX 1A

MEASURED DEFLECTIONS OF MODIFIED NASA STEPPED SPECIMENS

MATERIAL: 18 NICKEL GRADE 200TI MARAGING STEEL

DEFLECTIONS ARE MEASURED IN UNITS OF 0.001 INCH

CO-ORD	VALIDATION STAGES #2	#3	#4	#4X	#4G	#5	#6	#7	#8	#9	#9X	CO-ORD
1	.04	.03	.00	.00	.00	.02	.01	.00	.01	.02	.01	1
2	.09	.08	.07	.00	.00	.09	.07	.02	.03	.08	.07	2
A	.07	.09	.07	.00	.00	.10	.08	.02	.03	.08	.06	A
B	.09	.09	.09	.00	.00	.11	.09	.03	.03	.11	.09	B
C	.33	.29	.33	.00	.00	.40	.35	.09	.10	.34	.30	C
D	.51	.53	.60	.00	.00	.73	.62	.20	.27	.58	.55	D
E	.84	1.21	1.27	.00	.00	1.77	1.57	1.06	1.10	1.45	1.37	E
F	1.10	1.82	1.84	.00	.00	3.56	2.56	2.15	2.14	2.50	2.43	F
G	1.51	2.95	2.87	.00	.00	7.85	3.66	4.23	4.17	4.58	4.44	G
H	1.81	3.82	3.63	.00	.00	11.88	4.10	8.42	6.48	6.89	6.76	H
3	.01	.03	.00	.00	.00	.01	.02	.00	.00	.01	.02	3
4	.01	.02	.00	.00	.00	.00	.00	.01	.00	.02	.01	4
I	.00	.02	.00	.00	.00	.01	.01	.00	.00	.00	.02	I
J	.01	.00	.03	.00	.00	.05	.04	.00	.01	.02	.03	J
K	.18	.13	.10	.00	.00	.02	.15	.03	.02	.10	.08	K
L	.33	.29	.30	.00	.00	.14	.39	.07	.07	.30	.27	L
M	.64	.81	.82	.00	.00	.82	1.33	.50	.67	1.06	1.00	M
N	.89	1.34	1.31	.00	.00	2.28	2.28	1.31	1.55	1.93	1.89	N
O	1.31	2.38	2.28	.00	.00	6.12	3.42	3.03	3.44	3.89	3.76	O
P	1.61	3.22	3.01	.00	.00	9.89	3.84	7.13	5.76	6.20	6.10	P
5	.02	.03	.00	.00	.00	.00	.03	.01	.00	.02	.02	5
6	.04	.00	.02	.00	.00	.03	.05	.01	.01	.03	.01	6
Q	.05	.01	.03	.00	.00	.02	.04	.00	.01	.04	.03	Q
R	.02	.03	.00	.00	.00	.01	.01	.01	.00	.01	.01	R
S	.23	.25	.25	.00	.00	.35	.29	.10	.07	.28	.30	S
T	.40	.50	.52	.00	.00	.75	.59	.23	.22	.58	.59	T
U	.72	1.16	1.19	.00	.00	1.96	1.56	1.20	1.15	1.55	1.51	U
V	.95	1.77	1.78	.00	.00	3.87	2.49	2.36	2.21	2.62	2.58	V
W	1.37	2.89	2.83	.00	.00	8.44	3.56	4.85	4.40	4.85	4.74	W
X	1.67	3.79	3.65	.00	.00	12.75	4.08	9.47	6.97	7.44	7.34	X

APPENDIX 1B

MEASURED DEFLECTIONS OF MODIFIED NASA STEPPED SPECIMENS

MATERIAL: GRAIN-REFINED HP 9-4-20

DEFLECTIONS ARE MEASURED IN UNITS OF 0.001 INCH

CO-ORD	VALIDATION STAGES #2	#3	#4	#4X	#4G	#5	#6	#7	#8	#9	#9X	CO-ORD
1	.05	.03	.02	.02	.00	.02	.01	.00	.01	.01	.05	1
2	.03	.05	.01	.07	.01	.05	.03	.02	.03	.02	.04	2
A	.01	.01	.01	.08	.13	.07	.09	.12	.11	.09	.08	A
B	.02	.01	.05	.22	.30	.22	.25	.29	.27	.22	.23	B
C	.37	.41	.01	.16	.30	.15	.18	.24	.23	.06	.12	C
D	.62	1.06	.21	.18	.07	.14	.11	.03	.03	.26	.16	D
E	1.06	2.97	1.63	1.48	.55	.98	.89	.81	.79	1.15	.97	E
F	1.39	4.75	2.99	2.76	1.04	1.86	1.72	1.68	1.62	2.08	1.85	F
G	1.90	8.18	5.51	5.17	1.88	4.70	3.36	4.02	3.85	4.82	4.21	G
H	2.28	10.97	7.50	7.08	2.51	8.03	4.59	8.05	6.89	8.20	7.52	H
3	.00	.04	.01	.15	.11	.10	.15	.11	.15	.10	.18	3
4	.02	.03	.03	.13	.03	.09	.11	.07	.10	.08	.10	4
I	.00	.08	.00	.04	.12	.04	.00	.08	.04	.04	.02	I
J	.00	.12	.05	.20	.26	.20	.17	.24	.20	.16	.16	J
K	.34	.16	.03	.23	.28	.22	.11	.26	.20	.06	.11	K
L	.57	.73	.06	.00	.04	.03	.16	.05	.00	.21	.14	L
M	1.04	2.42	1.17	1.07	.60	.52	.95	.56	.68	1.00	.85	M
N	1.40	4.10	2.40	2.17	1.13	1.17	1.85	1.27	1.45	1.87	1.68	N
O	1.95	7.42	4.78	4.48	1.97	3.70	3.54	3.32	3.65	4.61	4.14	O
P	2.33	10.16	6.70	6.33	2.56	6.96	4.72	7.36	6.75	8.09	7.43	P
5	.02	.00	.02	.01	.03	.04	.02	.01	.02	.01	.26	5
6	.04	.01	.00	.03	.08	.00	.02	.01	.02	.01	.05	6
Q	.04	.04	.01	.09	.22	.12	.07	.15	.11	.08	.16	Q
R	.07	.01	.05	.21	.37	.24	.22	.29	.24	.18	.19	R
S	.51	.48	.01	.08	.28	.08	.03	.16	.12	.04	.09	S
T	.78	1.26	.32	.29	.01	.28	.30	.14	.18	.42	.20	T
U	1.27	3.41	1.88	1.74	.68	1.28	1.17	1.04	1.06	1.43	1.00	U
V	1.63	5.34	3.27	3.08	1.21	2.25	2.03	1.96	1.96	2.42	1.88	V
W	2.20	8.97	5.85	5.54	2.02	5.33	3.68	4.40	4.30	5.32	4.39	W
X	2.61	11.87	7.86	7.49	2.62	8.99	4.86	8.83	7.52	9.91	7.72	X

APPENDIX 1C

MEASURED DEFLECTIONS OF MODIFIED NASA STEPPED SPECIMENS

MATERIAL: PH13-8MO STAINLESS STEEL

DEFLECTIONS ARE MEASURED IN UNITS OF 0.001 INCH

CO-ORD	VALIDATION STAGES #2	#3	#4	#4X	#4G	#5	#6	#7	#8	#9	#9X	CO-ORD
1	.01	.03	.00	.00	.00	.03	.02	.00	.03	.01	.03	1
2	.04	.03	.09	.00	.00	.09	.13	.11	.11	.13	.12	2
A	.03	.01	.08	.00	.00	.09	.11	.09	.09	.10	.10	A
B	.07	.03	.02	.00	.00	.01	.02	.01	.00	.00	.00	B
C	.39	.30	.50	.00	.00	.67	.59	.60	.55	.62	.59	C
D	.61	.59	.92	.00	.00	1.16	1.04	1.06	.99	1.09	1.05	D
E	1.04	1.25	1.76	.00	.00	2.38	2.13	2.15	2.00	2.17	2.09	E
F	1.38	1.82	2.45	.00	.00	3.77	3.12	3.20	3.04	3.12	3.05	F
G	1.94	2.84	3.67	.00	.00	6.65	4.41	4.96	4.67	4.39	4.26	G
H	2.36	3.64	4.61	.00	.00	9.14	5.22	7.10	5.84	4.99	4.92	H
3	.02	.04	.06	.00	.00	.03	.00	.04	.03	.03	.03	3
4	.02	.02	.01	.00	.00	.01	.08	.05	.03	.07	.04	4
I	.00	.03	.00	.00	.00	.00	.04	.01	.01	.01	.00	I
J	.02	.01	.07	.00	.00	.11	.06	.07	.10	.12	.14	J
K	.26	.23	.59	.00	.00	.67	.68	.66	.64	.78	.77	K
L	.45	.47	.99	.00	.00	1.05	1.10	1.05	1.04	1.25	1.24	L
M	.86	1.08	1.83	.00	.00	2.03	2.17	2.03	2.00	2.38	2.33	M
N	1.18	1.63	2.55	.00	.00	3.29	3.21	2.98	3.01	3.33	3.31	N
O	1.75	2.67	3.84	.00	.00	6.07	4.75	4.67	4.73	4.74	4.63	O
P	2.17	3.49	4.85	.00	.00	8.56	5.65	6.80	5.92	5.34	5.33	P
5	.00	.05	.00	.00	.00	.00	.04	.00	.02	.04	.04	5
6	.01	.01	.09	.00	.00	.16	.07	.11	.12	.05	.07	6
Q	.01	.02	.14	.00	.00	.21	.15	.19	.18	.14	.15	Q
R	.06	.01	.24	.00	.00	.37	.27	.31	.32	.30	.30	R
S	.38	.28	.74	.00	.00	.99	.84	.88	.82	.85	.82	S
T	.60	.57	1.14	.00	.00	1.49	1.29	1.34	1.25	1.30	1.26	T
U	1.03	1.27	1.95	.00	.00	2.73	2.35	2.44	2.26	2.33	2.27	U
V	1.36	1.88	2.62	.00	.00	4.14	3.25	3.44	3.22	3.12	3.09	V
W	1.92	2.98	3.85	.00	.00	7.10	4.50	5.22	4.75	4.16	4.05	W
X	2.34	3.87	4.84	.00	.00	9.67	5.29	7.45	5.88	4.62	4.57	X

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-172450		

4. Title and Subtitle
MACHINING - INDUCED DEFORMATION IN STEPPED SPECIMENS OF PH 13-8 Mo, 18 NICKEL MARAGING STEEL GRADE 200T1 AND GRAIN-REFINED HP 9-4-20

5. Report Date
June 1985

6. Performing Organization Code

7. Author(s)
D. A. Wigley

8. Performing Organization Report No.

9. Performing Organization Name and Address
Kentron International Inc.
Hampton Technical Center
3221 North Armistead Avenue
Hampton, VA 23666

Sub-Contractor
Cryo Support Services Inc.
P.O. Box 765
New Castle, DE 19720

10. Work Unit No.

11. Contract or Grant No.
NAS1-16000

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, DC 20546

13. Type of Report and Period Covered
Contractor Report

14. Sponsoring Agency Code
505-31-53-11

15. Supplementary Notes
Dr. D. A. Wigley is president of Cryo Support Services, Inc.
Langley Technical Monitor: Dr. Clarence P. Young, Jr., Charles E. Cockrell

16. Abstract

This report documents the results of a study to evaluate the dimensional changes created during machining and subsequent cycling to cryogenic temperatures for three different metallic alloys. Experimental techniques are described and results presented for 18 Ni Grade 200 maraging steel, PH-13-8 Mo stainless steel, and Grain-refined HP 9-4-20.

17. Key Words (Suggested by Author(s))
Cryogenic Wind Tunnel Models
Machining - Induced Stress
Dimensional Stability
Machining Effects on Metallic Alloys
Cryogenic Materials

18. Distribution Statement
Star Category - 26

Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	33	A03

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