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A SYSTEMATIC PLAN FOR THE
CONTINUED STUDY OF DIMENSIONAL
STABILITY OF METALLIC ALLOYS
CONSIDERED FOR THE FABRICATION
OF CRYOGENIC WIND TUNNEL MODELS

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1. Introduction

The advent of large cryogenic wind tunnels such as the National Transonic Facility (NTF) has created many challenges for the designer of models. Research and development programs have been set up to investigate various areas of technology relevant to the fabrication of these models. One particular area of concern lies in the dimensional instability that occurs in some alloys due to the creation of residual stresses. These stresses can be created during fabrication and relieved during subsequent heat-treatment at high temperatures or on cooling to their cryogenic operating temperatures. A simple stepped specimen configuration has been utilized as a basis for the systematic evaluation of the stresses created or relieved by various fabrication processes. Initial results are described in Ref. 1. Further details of the proof-of-concept tests on an 18 nickel 200 grade maraging steel sample are given in Ref. 2. The results of further work on 17 stepped specimens are presented in detail in Ref. 3. A critical evaluation of this work on A286, PH13-8Mo and 18 nickel 200 grade maraging steel led to the decision to lengthen the unmachined 12mm thick section of the specimens from 12 to 72 mm. This allowed reproducible leveling of the reference surface to be achieved. A further three specimens, grain-refined HP 9-4-20, a cobalt-free 18 nickel 200 grade maraging steel and a PH13-8Mo stainless steel, have been subjected to a series of milling, grinding and cryocycle stages to evaluate the modified specimen configuration. The results are given in Ref. 4.

A number of other R & D activities are also being carried out in support of the cryogenic wind tunnel model technology development program. (Refs. 5-8) In particular, bonding and filler systems capable of cryogenic service are under intensive development. These are designed both for making permanent bonds as well as easily demountable joints. A program on toughness enhancement by grain refinement is also under development.

State-of-the art information on Cryogenic Wind Tunnel model technology may be found in a number of recent conference proceedings, Refs. 9-13, and in other AGARD and AIAA conference proceedings, while the more general cryogenic properties of materials are discussed in Refs. 13 & 14.

2. Background

Designers often experience considerable difficulty in finding the information they need to design and fabricate wind tunnel models, partly due to the very fragmented location of such information. Furthermore, much useful knowledge is often lost to the technical community as a whole when pressure of work, or a change of responsibilities, prevents adequate technical documentation of both successful and unsuccessful airfoil or model designs.

Although somewhat idealized, Fig. 1 shows a schematic representation of the way in which information on the many factors involved in the design and construction of such models may be generated, stored and transmitted. At the conceptual design level, the constraints set by the aerodynamic, aeroelastic and instrumentational considerations require the input of data contained in the various locations shown in the "Information Sources" box. Further, more detailed, information is required on the next phase when a general specification and design study is undertaken. These include material properties, information on shaping and joining technologies, together with the cost and availability of candidate materials.

Once fabrication of a specific model is undertaken, some information on the experience gained should start to flow back via feed-back paths to enhance the cumulative knowledge on both successful and unsuccessful techniques used. Once the model has been put into operation, further feed-back should enable its performance and degradation to be monitored. Modifications or the adoption of alternative configurations should also provide valuable opportunities for data feed-back. Finally, once a model has reached the end of its useful life, some form of post-mortem examination would allow comparison of the initial model design with its subsequent performance.

Many sources of relevant information may be tapped to provide the breadth and depth of data that will be needed if models for cryogenic wind tunnels are to be fabricated more efficiently. Experience generated from other models in conventional as well as cryogenic wind tunnels could be supplemented by that from other relevant technologies in the U.S.A. and overseas. Some problems would, however, require specific research and development programs for their solution. Three examples of particular current relevance are; (1) toughness-enhancement by grain-refinement, (2) bonding and filler materials, and (3) the stepped specimen project. All thre projects are designed to supply information on the candidate materials for cryogenic wind tunnel model construction. The embodiment of this accumulated knowledge in a "Handbook of Cryogenic Wind Tunnel Model Technology" would be a valuable source for model designers.

3. Interrelated Research & Development Activities

As noted earlier, three specific activities are currently receiving much attention and their scope is shown schematically in figure 2. For each candidate material, a large number of often-interrelated topics have to be understood. The stepped specimen has been proposed as a simple configuration that would allow the various fabrication technologies to be evaluated. Initial tests have already shown that milling and grinding induce compressive and tensile surface stresses respectively. These stresses are much larger in austenitic steels such as A286 than in the 18Ni grade 200 maraging steel. Cryocycling samples after machining has also enabled their cryostability to be investigated.

Further experimentation should enable this work to be extended to study stress relief by heat treatment, possible degradation by fatigue and corrosion, as well as stress-free machining techniques such as chemical milling and electrodischarge machining. Larger and more representative samples would be necessary to investigate any scale effects. The bonding program is shown as two separate zones, one for metallic systems such as soldering and brazing, and the other for non-metallic systems such as adhesives. Overlap with the stepped specimen program occurs in areas such as heat-treatment, cryocycling, vibration and other environmental factors. The program to enhance toughness by grain refinement overlaps with the stepped specimen and bonding projects mainly in the area of heat-treatment as indicated in Figure 2. Specifically, it is essential that bonding or other heat-treatment is not carried out at temperatures that allow grain growth, or other forms of degradation such as sensitization in 300 series stainless steels.

Although there are likely to be some generic links between the behavior of different classes of materials, it is probably clearer to group the information together according to the specific material under study. Thus, in Figure 3, the lead material is taken to be 18Ni Grade 200 maraging steel and the information generated by the bonding and dimensional stability studies is shown as being applied to the construction of representative segments and actual 2D and 3D models.

A286 is taken to be the second material under study with its own dimensional stability and bonding programs, represented schematically as an ellipse and two hexagons. Subsequent materials shown listed would also be expected to have separate programs of a scope relative to their potential usefulness.

4. Phased Development of a Stepped Specimen Program

A more detailed representation of a possible phased development of dimensional stability studies using stepped specimens is illustrated in Figure 4. The locations of the different technologies within the elliptical outline of the schematic program are the same as in Figure 2. More information is, however, shown for the various parameters, such as process variables, that might be considered during a more thorough investigation into each area. Furthermore, the phased development of the project is represented by the progressive increase in length and breadth of the knowledge vector which spreads out in the direction of each of the different technologies. Thus, for Material 1, three phases of development are shown A, B and C, as this is assumed to be the most intensively studied alloy. Material 2 is shown as having completed only phases A and B, while Material 3 has only gone through phase A, suggesting that the need for data on these materials is less immediate than that for Material 1. Although it does not emerge clearly from this schematic diagram, it should be noted that it is not necessary for all technologies to be investigated to the same extent within a given phase, nor is it strictly necessary for the breadth or depth of the study of a particular technology to be the same for each material.

5. Summary of Dimensional Stability Studies

At present three phases of work have been completed or are still in progress and salient features are summarized in Figure 5, together with an outline of possible future work. The dashed ----- line around the upper left hand corner of Fig. 5 indicates the limits reached during the initial phases of the program. Specimens sized 60 x 60 x 12 mm thick were used for phases 1 and 2, but the location of the third leveling point on a part of the specimen that was subsequently machined created a false impression of the induced deflections. Comparison of successive processing stages was also difficult and it was therefore decided to extend the specimen length to 120 mm while leaving the machined steps the same size. This effectively created an undisturbed leveling surface which also contained within it the center of gravity of the specimen. Phase 3 utilized three of these modified specimens which were machined in a specially designed fixture intended to reproduce as closely as possible the way in which an actual model wing would be supported during fabrication. Use of a computer-controlled validation table enabled many, closely-spaced data points to be taken from the reference surface. This large amount of data not only allowed the plotted deflections to be represented by continuous lines, but it also enables the magnitudes of the surface stresses to be calculated from those segments of the beam that correspond to circular arcs. The results obtained from Phase 3 clearly demonstrate the advantages of the modified specimen configuration, as well as giving valuable data on the three test materials.

6. Schematic Sequence for a Specific Program of Machining, Validation and Heat-Treatment Cycles on one Material

In the initial trials a set sequence of rough machining, heat-treatment, milling and grinding operations were carried out on each sample prior to cryocycling. It is now appropriate to separate out these operations so that a more detailed appreciation of their individual effects can be built up. Figure 6 shows schematically how two different samples might be used to investigate the creation and relief by heat-treatment of the distortion introduced by milling and grinding operations. Furthermore, additional information could be obtained from a simple extension to the program by comparing samples machined using carbide and high speed steel cutters, or by contrasting the effect of using new and partially worn cutters.

Consider first the stepped specimen to be used for milling tests. After initial shaping and lapping the reference surface, the first validation stage would establish the datum surface, indicated as M, from which subsequent distortion would be measured. The appropriate milling stage would then be carried out, as is shown labeled 1st Mill on the milling vector. Revalidation would now be expected to show that the compressive stresses induced during milling have created positive strains of magnitude represented by the first upward pointing arrow along the V1 vector.

As the materials to be evaluated in this program are for potential use in fabricating cryogenic wind tunnel models, it is appropriate to check whether machining has introduced any microstructural changes or other factors which might adversely affect its dimensional stability when cycled cryogenically. Three ambient - liquid nitrogen - ambient temperature cycles are therefore carried out at this stage followed by revalidation to check for dimensional stability and to re-establish the reference surface for subsequent stages of the program. Assuming that heat-treatment for time t1 at temperature T1 allows some stress relief, revalidation would then give the magnitude of the remaining strain, represented by the smaller upward arrow on the V1 vector. A further heat-treatment at temperature T1 for time t2 should allow additional stress relief, while revalidation at this stage would allow measurement of the residual strain.

By connecting these validation, machining, cryocycle and heat-treatment stages with dotted lines, as has been done in Figure 6, the sequence of events may be followed quite easily.

If the residual strains are now assumed to be minimal, a second milling operation would set up further compressive stresses and the resultant induced strains would be measured during a second validation cycle, again represented by an upward pointing arrow at V2. Cryocycles, revalidation, then heat-treatment at a different temperature T3 for time t3, followed by revalidation would enable the effect of this heat-treatment on strain recovery to be evaluated. By careful choice of milling steps a number of different heat-treatments could be evaluated using the same sample. The exact times and temperatures would depend on the particular material chosen, but in general temperatures low enough to avoid sensitization, precipitation hardening or grain-growth, yet high enough to give worthwhile stress-relief, would be of practical importance.

7. Proposed Work to be Performed in the Next Phase

A number of samples of 18Ni 200 grade maraging steel, A286 and 13/8 Mo stainless steels remain from previous experiments. It is suggested that they might be used to provide some initial data on annealing heat-treatments as they all still have some degree of stress-induced deformation that should be thermally recoverable. A possible sequence of operations might be

- Revalidate surface profile of specimen, check structure and hardness
- Put through 1st temperature/time combination heat-treatment
- Revalidate profile, recheck hardness, etc.
- Increase temperature and/or time of heat-treatment
- Revalidate profile, recheck hardness, etc.

The actual temperatures and times chosen would vary from material to material. Thus, for example, in the case of the 18Ni maraging steel, heat-treatment would have to be below or above the age hardening temperature range, while for austenitic stainless steels the sensitizing temperature range needs to be avoided. It would be particularly valuable to establish whether or not worthwhile stress relief can be obtained in austenitic stainless steels at temperatures below their sensitizing range as this would allow intermediate process annealing between machining stages. Such a program would correspond to Phase 4 of the sequence summarized in Figure 5 and use about 10 of the old specimens.

A more thorough program would be needed to study the interrelationships between the dimensional instability created by machining-induced stresses, and the temperatures and times needed for its recovery by heat-treatment. A possible starting point for such a program might be as follows:

- Choose A286 and V200 as "state of the art" materials for constructing models for cryogenic wind tunnels.
- Carry out separate, parallel programs for milling- and grinding-induced damage plus control program on stress-free machining.
- For each material and each stress-inducing machining technique:
    - check microstructure and hardness of sample, prepare surface and validate;
    - choose appropriate set of machining parameters;
    - machine step into pre-prepared and validated slab to give easily measurable stress-induced distortion;
    - revalidate surface profile of distorted specimen;
    - carry out intermediate temperature stress-relieving heat-treatment for particular choice of temperature and holding time;
    - revalidate surface profile of specimen.

-depending on degree of recovery, then either repeat heat-treatment for different combination of time and temperature, or, if recovery complete, proceed to different machining schedule.

Approximately 4 samples of each material would be needed to make a worthwhile start on such a program. It would correspond to Phase 5 of the sequence summarized in Figure 5.

8. Proposed Further Technology Development Activities

In both figures 2 and 3 a sector is shown labeled "APPLICATION" and within it is indicated a progressive increase in sample size and complexity. Part of the scale-up has already been accomplished in going from the original 60x60x12mm specimen to the current 120x60x12mm, which should now become the standard configuration for future work. Nevertheless, there are good reasons for believing that some work should be carried out on larger samples to help bridge the gap that would otherwise exist between the standard samples and real 2D and 3D airfoils. A logical development would be to double all dimensions to give samples sized 240x120x24mm while retaining the basic stepped specimen configuration. This would allow the use of 1-inch thick plate as the source material for these larger samples.

A further area needing attention concerns stress balancing. One way of minimizing warpage is to take cuts alternately from opposite sides of the object being machined. This, in effect, creates equal stresses in the two surface layers which balance each other out and prevent warpage, although in more complex configurations exactly similar treatment of both surfaces is not possible. Furthermore, the initial results from phases 1 - 3 of this program have shown that while milling introduces compressive surface stresses, grinding creates tensile surface stresses. Thus, there is a possibility of being able to correct stress-induced warpage by inducing further compressive or tensile stresses into one or other of the surfaces to restore the workpiece to its correct dimensions and profile.

Quantitative evaluation of the machining schedules necessary to correct previously induced dimensional changes could be carried out on either the standard 120x60x12mm or the larger 240x120x24mm single sided specimen by carrying out all machining operations on one side of the specimen and all measurements on the opposite, undisturbed validation face. Furthermore, as long as the reference surface remained undisturbed, it would be possible to machine tapers, one or two dimensional curved surfaces, networks of channels, or any other meaningful shapes into the work surface to evaluate their effect on the dimensional stability of the sample. Interpretation would, however, be more difficult with these complex configurations and more data points would be needed to establish the profiles of the reference surface.

Detailed investigation of stress balancing by machining alternate faces would however need a modified specimen configuration, some possible examples being shown in Figure 7. The central problem here would be to create validation surfaces, probably at the edges and thin end of the sample, that would give a true indication of the movements of the opposite surfaces as they were alternately machined. Of the two basic configurations suggested in Figure 7a and b, the use of thin strips fixed into slots cut in the sides and ends of the sample would probably be most cost-effective, but the presence of the slits might create edge effects that would become more serious as the sample thickness decreased.

If these modified specimens were shown to give valid and reproducible results, further adaptation might allow the development of sample configurations even more representative of the shape of 2D or 3D airfoil models.

9. Conclusions

Any work carried out within the proposed program would naturally follow the pattern established during the early phases and be documented for publication as NASA reports or other conference proceedings as appropriate. Nevertheless, as indicated earlier, a major long-term benefit would be to have the work from the stepped specimen, bonding, grain-refinement and other specific R & D project correlated with the information generated from other sources and compiled into a reference work provisionally entitled the "Handbook of Cryogenic Wind Tunnel Model Technology". Ideally, early commitment of resources to such a project would give its achievement the greatest chance of success. In the possible absence of such firm commitment it would, however, be worth holding its eventual production as an objective and taking steps to ensure that work carried out in the meantime was structured and presented in such a way as to facilitate its eventual incorporation into a work of reference such as that proposed.

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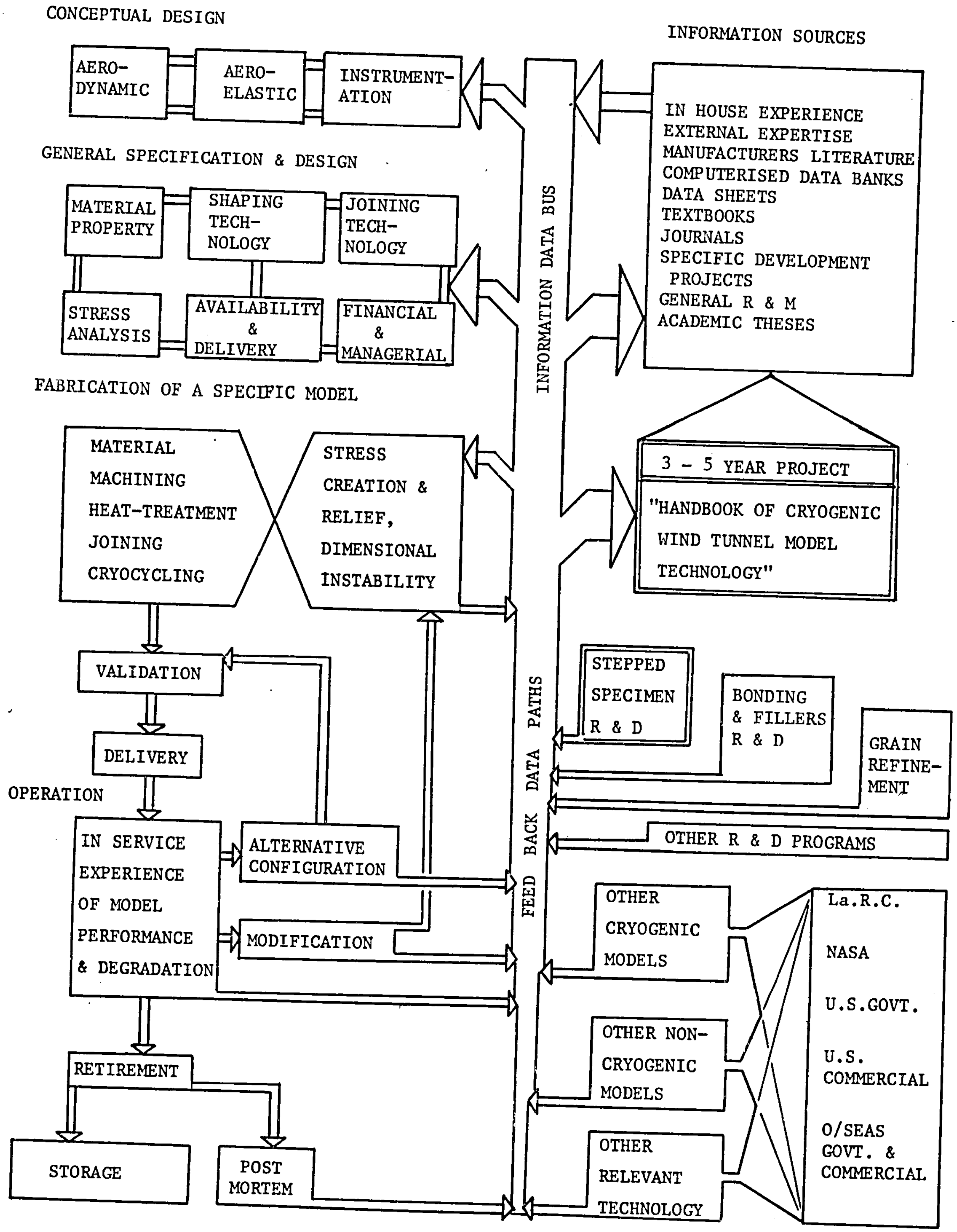

FIGURE 1 SCHEMATIC REPRESENTATION OF IDEALIZED INFORMATION TRANSFER PATHS IN THE DESIGN AND CONSTRUCTION OF CRYOGENIC WIND TUNNEL MODELS

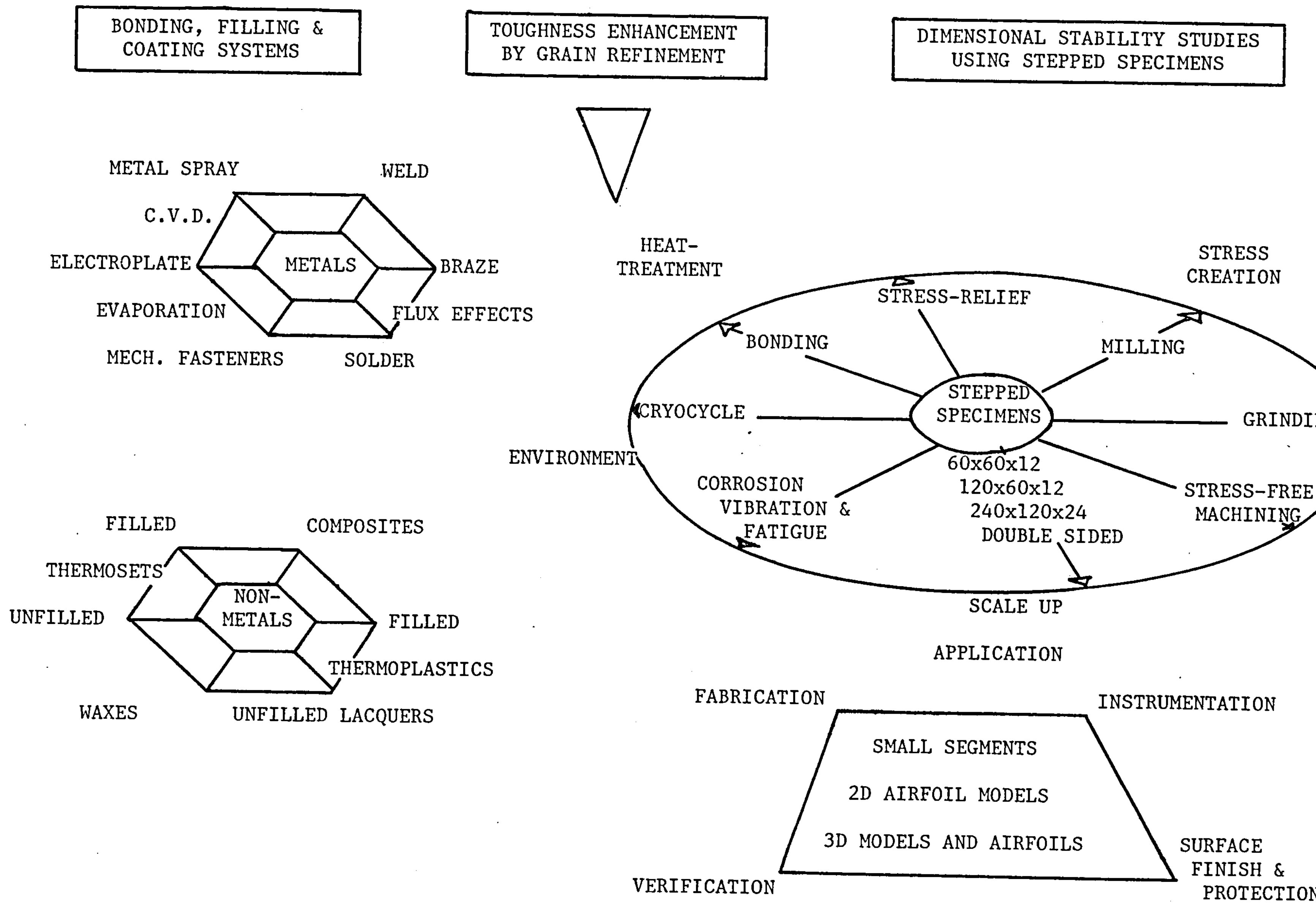

FIGURE 2 SPECIFIC R&D PROJECTS TO SUPPORT CRYOGENIC MODEL PROGRAM

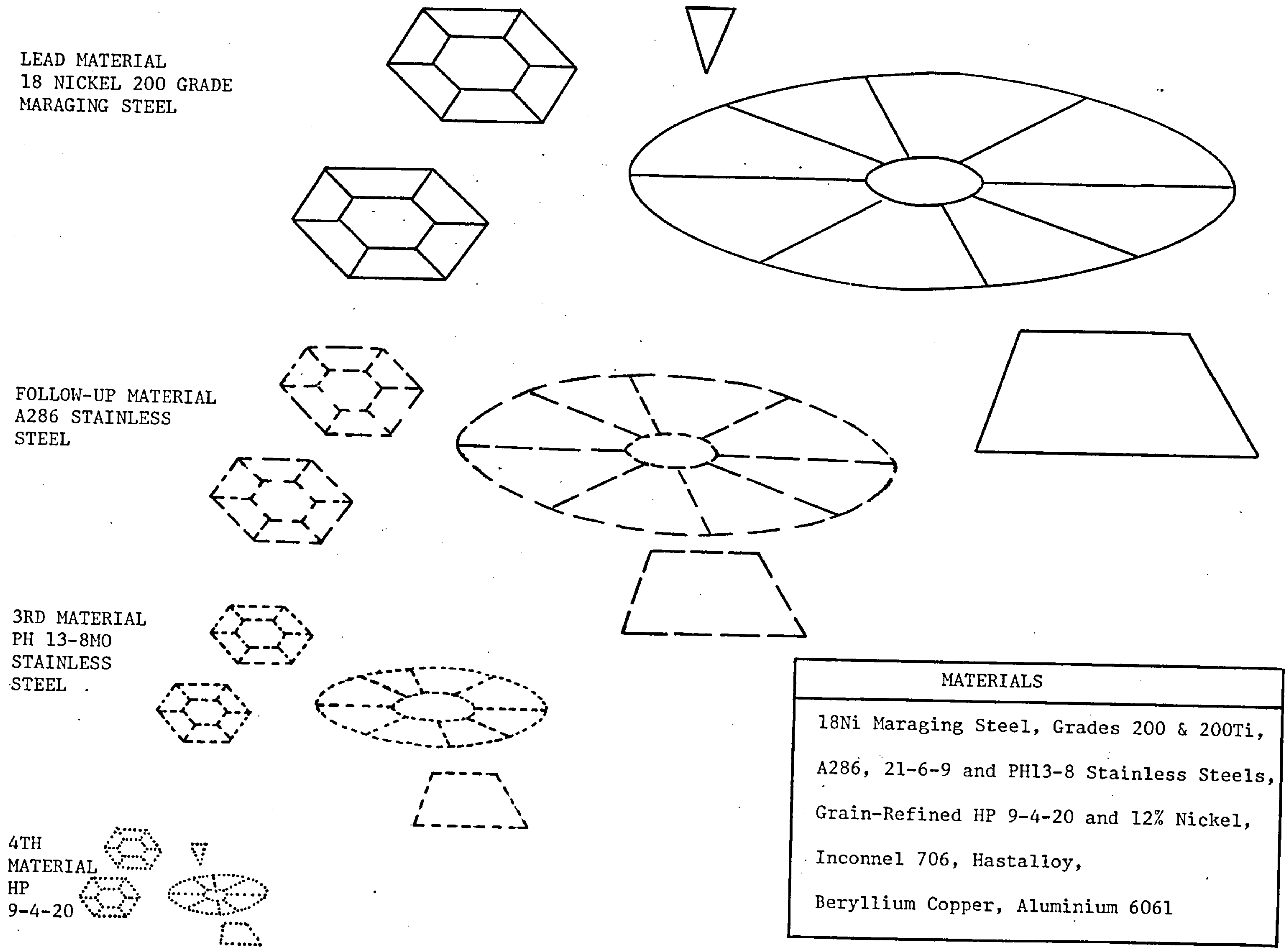

FIGURE 3 PROGRESSIVE INVOLVEMENT OF DIFFERENT MATERIALS IN SUPPORT OF CRYOGENIC MODEL PROGRAM

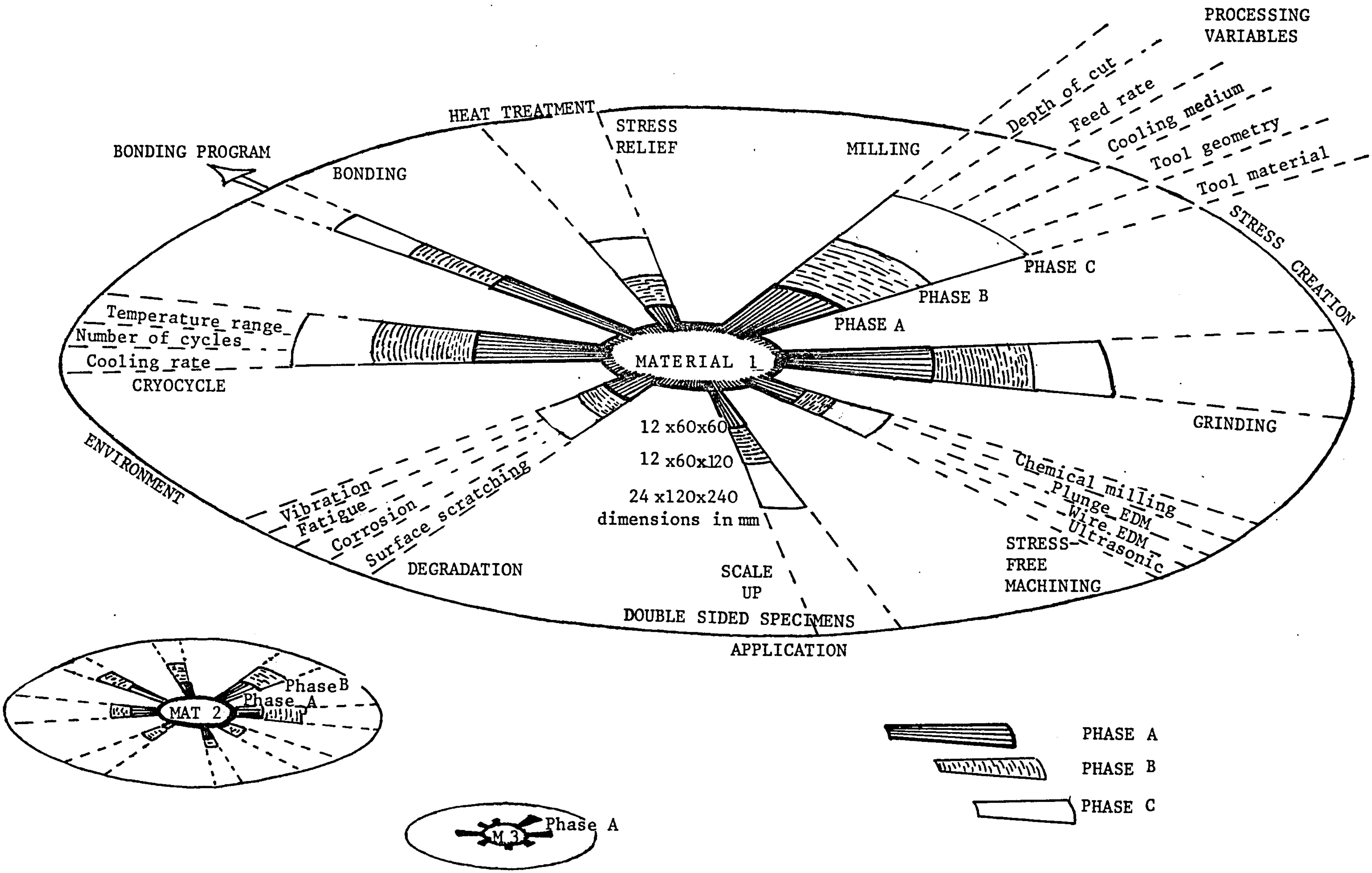

FIGURE 4 PHASED DEVELOPMENT OF THE STEPPED SPECIMEN PROGRAM

Phase	Material, size and No. of specimens	Stress Characterization and Measurement	Cryocycle Stability	Stress Minimization	Thermal Recovery	Stress Balancing
1.	1 x V200 60x60x12mm	Milling-compressive, ∿5-10Ksi Grinding-tensile?:	Good	-	-	-
2.	6 x V200 7 x 13-8Mo 4 x A286 all 60x60x12mm	Milling-compressive: Grinding-tensile: No strong orientation or surface/center effects	A286-excellent V200-good 13-8Mo-suspect	- - -	- - -	- - -
3.	1 x V200T 1 x HP9-4-20 S9R 1 x 13-8Mo all 120x60x12mm	Use of machining support; semi-continuous computer-controlled data collection: validation & stress measurement during coarse and fine machining:	Good Suspect Suspect	- - -	- - -	- - -
4.	4 x V200 4 x 13-8Mo 2 x A286 all 60x60x12mm	Revalidate existing Phase 2 specimens: heat-treat and revalidate to establish rough temp-time-recovery properties:	- - -	- - -	<925F or >1500F <1150F <1100F?	- - -
5.	4 x V200 4 x A286 all 120x60x12mm	Use 3 ball end mill only and 1 grind only: quantitative results	Check after each stage	Effect of cutter type and wear	<925F or >1500F <1100F?	- -
6.	V200 A286 240x120x24mm 120x60x12mm	Scale up stepped config'n: 1 and 2D tapers on one side leaving flat for validation: Special config'n for double sides:	Check at all stages	?	?	- - √

- - - - - Limit of existing programs.

FIGURE 5 SUMMARY OF PAST AND PRESENT PROGRAMS TO UNDERSTAND AND CONTROL MACHINING-INDUCED STRESSES AND DIMENSIONAL INSTABILITY, WITH A PROJECTION OF FUTURE DEVELOPMENTS

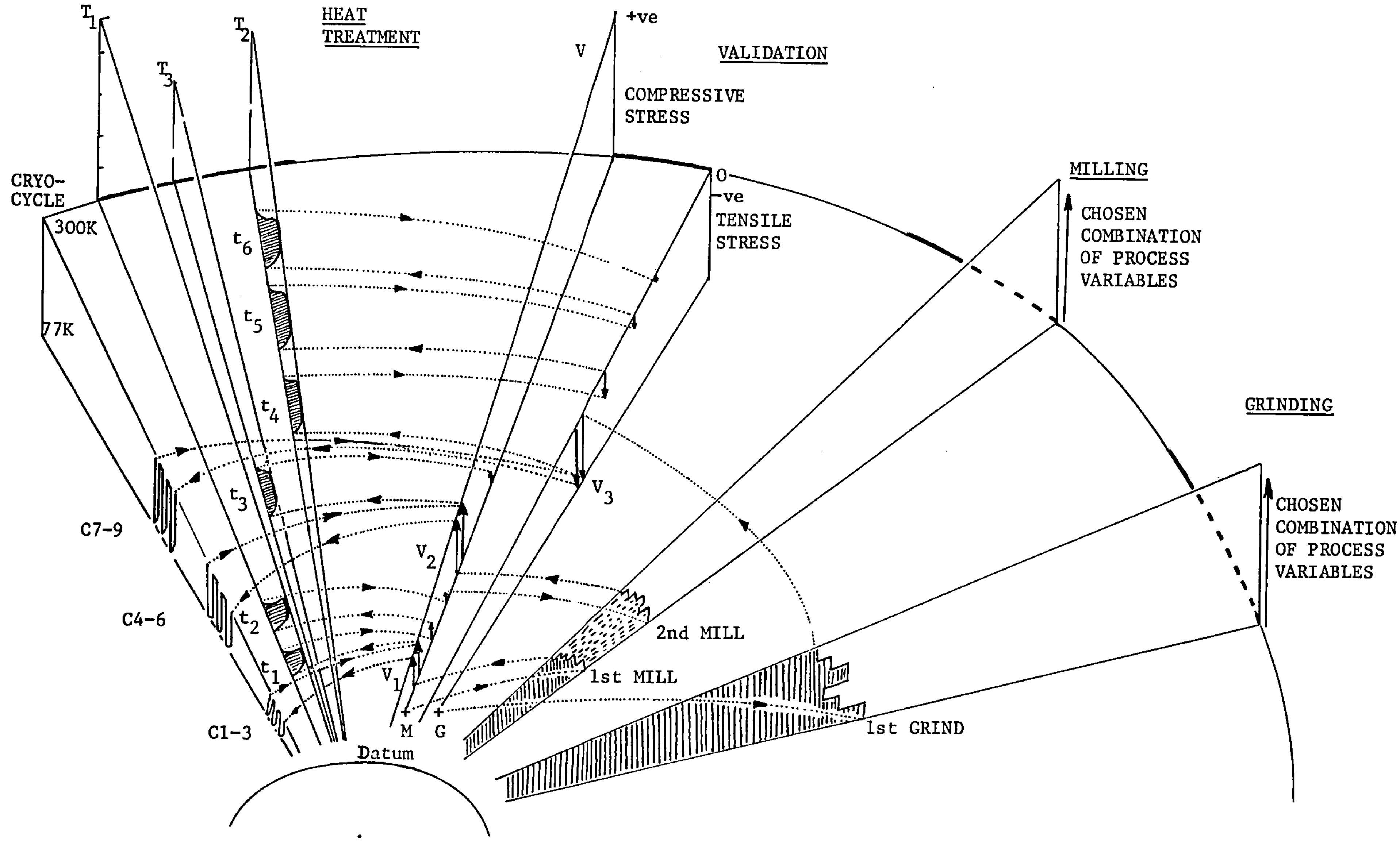

FIGURE 6 SCHEMATIC SEQUENCE FOR A PROGRAM OF MACHINING, VALIDATION, CRYOCYCLE AND HEAT-TREATMENT CYCLES

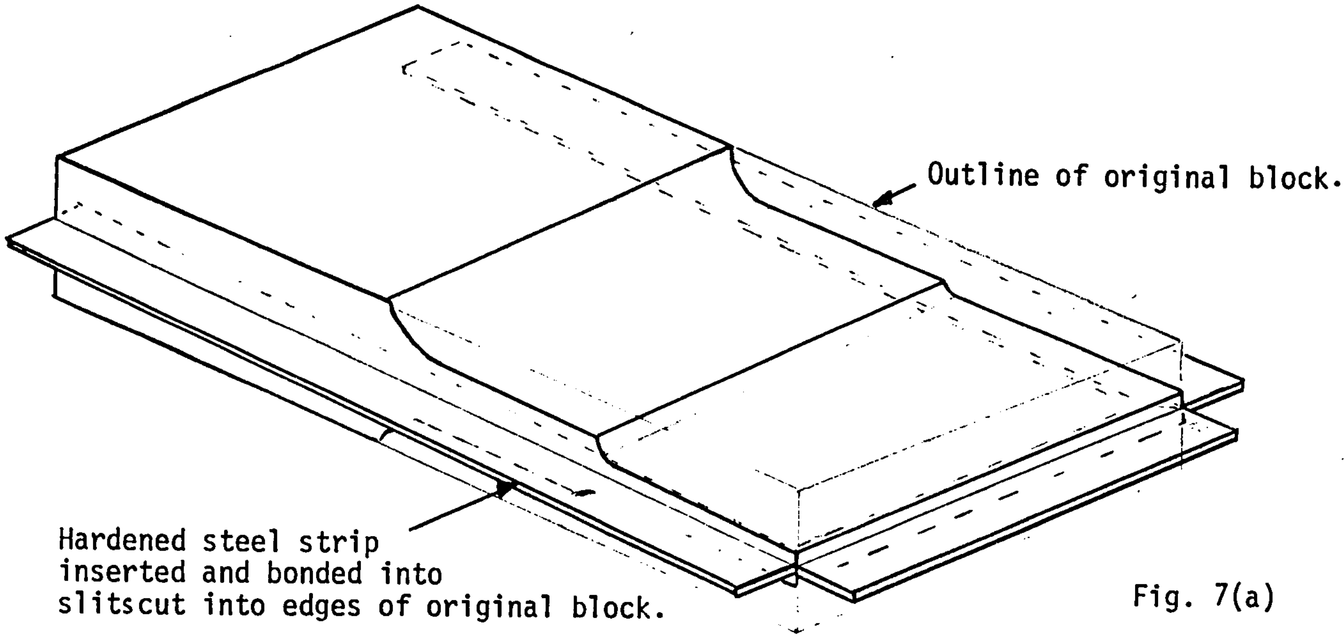

Fig. 7(a)

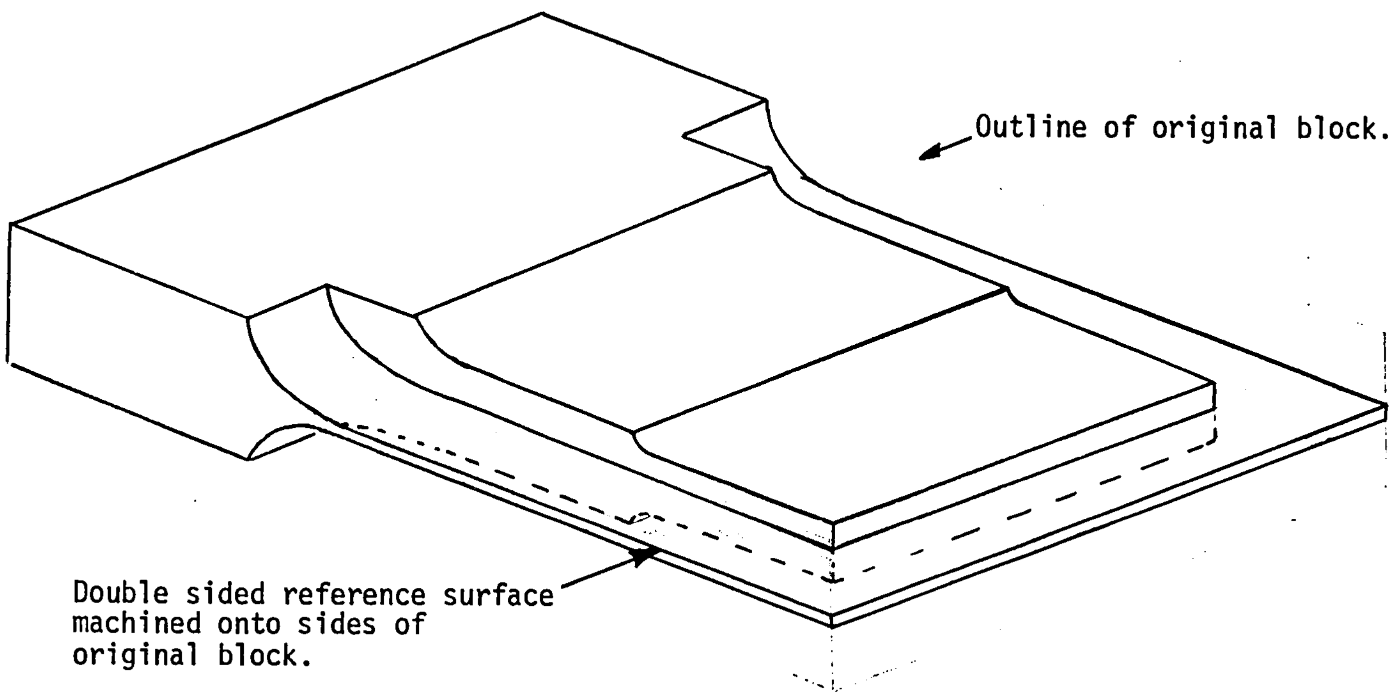

Fig. 7(b)

FIGURE 7 TWO POSSIBLE EXAMPLES OF MODIFIED STEPPED SPECIMEN CONFIGURATIONS THAT WOULD INVESTIGATE STRESS BALANCING BY MACHINING ALTERNATE FACES

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15. Supplementary Notes

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16. Abstract

This report documents interrelated research and development activities, phased development of stepped specimen program and describes a sequence for a specific program of machining, validation and heat-treatment cycles for one material. Proposed work for the next phase of dimensional stability research is presented and further technology development activities are proposed.

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