DEVELOPMENT OF A BEAM BUILDER FOR AUTOMATIC FABRICATION OF LARGE COMPOSITE SPACE STRUCTURES

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ABSTRACT

This paper describes the composite material beam builder concept currently being designed and developed for NASA Lyndon B. Johnson Space Center.* The machine will produce triangular beams from pre-consolidated graphite/glass/thermoplastic composite material through automated mechanical processes for forming; side member storage, feed and positioning; ultrasonic welding; and beam cutoff. Each process lends itself to modular subsystem development. Initial development has been concentrated on the key processes for roll forming and ultrasonic welding composite-thermoplastic materials. The construction and test of an experimental roll forming machine and ultrasonic welding process control techniques are described.

INTRODUCTION

In the ensuing years with the advent of the Shuttle Transportation System, the use of robots will play an indispensible role in the on-orbit construction of large space systems. It will be neither practical nor feasible to use men to perform highly repetitive precision assembly operations that can be accomplished quickly and efficiently by automated machines. Advances in microelectronics coupled with the technology developed for spacecraft mechanisms has paved the way for a new and challenginig field of space fabrication and assembly equipment.

Current studies of advanced space systems generally indicate that a basic piece of equipment required for on-orbit fabrication of large space structures is an automated beam fabrication machine. This beam builder must produce numerous structural beams from materials stored in small volumes within the machine. The beams are then joined together by automatic assemblers into large structures.

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The beam builder concept described herein fabricates beams from graphite/glass/ thermoplastic composite material. This machine has two key processes which have been evaluated experimentally to prove viability of the concept. The first is the forming process for beam cap members. Some of the problems encountered during prototype cap forming machine development are discussed. The second key process is ultrasonic welding. The advantages of ultrasonic welding are discussed along with its unique process control capabilities.

BEAM BUILDER CONCEPT

The design of a beam builder is primarily determined by the configuration of the beam it must build. The beam design must also be adaptable to automatic manufacturing processes. The beam builder concept of Figure 1 resulted from numerous trade studies of beams and beam fabrication and assembly processes as described in Reference 1. The size and arrangement of this beam builder were established to permit fabrication of a 200m x 11m planar ladder platform in a seven day mission using the Space Shuttle Orbiter as a construction base. The overall machine concept was selected to permit scale-up to a wide variety of beam sizes. This machine has an estimated weight of 3600 kg, including 1000 kg of material, and has a 2 kw average power requirement.

The beam is manufactured from three basic elements, i.e., caps, cords and crossmembers. Open section caps are formed in continuous lengths from long coiled flat strips of pre-consolidated single-ply graphite/glass fabric in polysulfone resin with a special outer coating for radiation protection. Pre-fabricated crossmembers of the same material are stored in clips. Six diagonal fiberglass cords impregnated with polysulfone resin are stored on spools. The beam is manufactured in a cyclic feed operation whereby the cap is driven for 40 seconds to advance the beam one bay length, then stopped for 40 seconds during assembly as illustrated in Figure 2. To build beams continuously would greatly increase the size and complexity of the machine because all assembly operations would have to be placed on a reciprocating carriage to move with the caps. Another advantage of cyclic feed is that faults detected during the assembly period can be corrected without elaborate backout sequences.

The beam builder system is designed with modular subsystems for cap forming, joining, cord positioning and tensioning, crossmember feed and positioning, beam cutoff, and control. A welded aluminum structure provides a chassis on which to mount these modular elements. This approach allows each subsystem to be independently developed, manufactured and checked out before being integrated into the beam builder system. It also simplifies the task of scaling the machine up to produce larger beams.

CAP FORMING MACHINE CONCEPT

The preliminary design concept of the cap forming machine is shown in Figure 3. This machine is sized to manufacture a 1.434m bay length of cap per cycle with a storage capacity for up to 1000m of continuous cap length. Greater length and storage capacity are possible where required. Peak power required to operate this machine is calculated to be 474 watts.

The cap drive unit provides the pull force to move the material from the storage roll through the heating, forming and cooling sections. It also acts to advance the beam through the assembly sections and deploy it from the beam builder. Material is heated to the plastic state (218°C) along the bend zones as the material passes through the heating section. The material goes through a transition from flat to formed in the forming section. Strip heaters are provided in the forming section for start-up and for maintaining material forming temperature when the machine is operated in air. In vacuum where convective cooling is not present, these heaters are turned off during forming operations. Temperature is monitored for control through non-contacting infrared sensors. The cooling section contains retractable fluid cooled platens which are engaged during the 40 second pause cycle and retracted during the 40 second run cycle. The rational for the selected design approach for each of the cap forming machine functions is summarized in Table I.

PROTOTYPE CAP FORMING MACHINE DEVELOPMENT

Initial Design

Although roll forming graphite/thermoplastic composite material had been demonstrated by earlier experiments, it was clear that a fully automated prototype would be required to evaluate and refine the cap forming machine design. The prototype machine shown in Figure 4 was designed as an experimental breadboard with individual assemblies for heating, forming, cooling, drive and control. This provided total flexibility in alteration and adjustment of the configuration.

Cost considerations dictated that heating and cooling sections be scaled down to produce 60 cm of cap per cycle. The heating section shown in Figure 5 used ordinary tubular electric heaters. Temperature control was accomplished with surface contacting thermocouple sensors and commercial temperature controllers. Quartz lamp heaters were used throughout the forming section to maintain material forming temperature during operation in air.

One of the objectives was to minimize the length of the forming section and the number of forming stages required. The initial forming section design shown in Figure 6 used two forming stages. The pre-forming stage would partially form the bend radii and the final stage would complete the section. Smooth transition from flat to formed section is essential to prevent buckling and wrinkling in the heated bend zones.

The initial material to be evaluated was a laminate as shown in Figure 4. This combination provided the desired structural characteristics and low coefficient of thermal expansion. The glass fabric acted to impede transverse heat transfer while the longitudinal strands of graphite fibers promote heat transfer in the warp direction. These thermal characteristics minimize heating energy and maintain material forming temperature in the bend zones throughout the forming process.

Design Problems and Solutions

The first series of forming tests revealed two major problems in the design which produced very unsatisfactory results. The initial material configuration was not well suited for the process and the forming section configuration was incorrect. The outer glass laminae were compressed and delaminated by the bending along the inside radii of the cap. This caused high drag loads to be created as the material passed through the forming rollers which distorted the formed section. The fine weave glass layers also acted to impede heating making it difficult to control heat rates without scorching the surface of the material.

The pre-forming rollers could not react the twisting moment induced by the unheated strip of material along the side of the cap. This caused the material to eventually be lifted out of the side rollers. As seen on the left in Figure 7, the side radii did not form and the material became bunched-up at the apex.

The breadboard design proved its worth by allowing the roller styles and arrangements to be altered conveniently. Each variation produced a better understanding of how to control the behavior of the material in the forming section. Through trial and error a smooth and stable transition from flat to formed was produced as seen in Figure 8 and a satisfactory cap member could now be formed.

The prototype cap forming machine is a useful tool for revealing very subtle problems associated with various weaves and laminates. One example is that of a single ply weave which had good heating and forming characteristics but poor cooling characteristics. The finished cap showed the result of what could be termed "spring-in" when cooled. The apex angle of the cap formed from this interim material would cool to a shape such that the apex angle was less than 60^{o} as shown on the right of Figure 7. Efforts to refine and evaluate detail material characteristics are continuing.

ULTRASONIC WELDING

Ultrasonic welding of thermoplastic materials has been used in the manufacture of commercial products for years. It is ideally suited for the assembly of composite/thermoplastic space structures because it produces solid joints, uses little energy, produces no debris or outgassing, and has fully automated process control for high reliability.

The beam builder concept employs six ultrasonic welders for joining the beam members together. Welder process controls are shown in the Figure 9 schematic. The weld head consists of a transducer which converts a 20 KHz power signal into ultrasonic vibrations which are transmitted to a metal horn at the half wave resonant frequency of the horn. The horn vibrates axially at both ends at an amplitude fixed by the amplitude output from the transducer. The crossmember and cap are firmly clamped between the horn and a backup anvil by a force applied by the welder drive mechanism. In this case the horn is equipped with three weld tips which impart vibration in the spots to be joined. The vibration quickly heats the thermoplastic resin in the mating surfaces of the parts to be joined to the plastic state. The power to the transducer is turned off and the parts are held clamped together until the thermoplastic solidifies creating a fused bond in the weld zones. A typical weld requires approximately 1 second of excitation and 0.5 second for cooling.

Manufacturers of ultrasonic welders indicate that the process can be controlled by three feedback signals. A load cell measures applied force. The resonant frequency of the horn is monitored directly for slight changes which occur due to temperature change. The amplifier will vary the frequency input to the transducer to maintain resonance of the horn. Finally, the power output of the horn is measured and compared with the amplifier power output. Weld time is automatically varied to allow the proper amount of energy to be input to the weld. Verification and control of these three critical parameters ensures the quality of the finished weld is within acceptable limits. Experiments with candidate hybrid composite/thermoplastic materials have produced excellent results with samples welded in both air and vacuum.

CONCLUSIONS

1. One of the most critical design factors to consider for space construction equipment such as the beam builder will be to provide the software and sensors necessary to ensure positive process control, fault analysis and fail safe operation.
2. The viability of the composite material beam builder concept is firmly supported by the demonstrations performed with its two key processes, the cap forming machine and the ultrasonic welding process.
3. Roll forming of composite/thermoplastic material requires careful selection and verification of material characteristics in order to be compatible with the machine processes. Similarly the machine processes must be tailored for the material to achieve satisfactory operating results.

REFERENCES

1. Browning, D. L., et al, "Space Construction Automated Fabrication Experiment Definition Study (SCAFEDS)," General Dynamics Convair Division, Final Report CASD-ASP77-017, NAS9-15310, May 1978, pp 2-36 thru 2-82.

Table I. CAP FORMING MACHINE CONCEPT SELECTION

FUNCTION	SELECTED APPROACH	RATIONALE

STORAGE	ROLL IN A CAN	• POSITIVE CONTAINMENT
		• NO REEL TO DISPOSE OF
		• HEATERS INTEGRATED
		  • MINIMIZES MACHINE LENGTH
		  • WASTE HEAT RADIATES TO ROLL
		• EASE OF REPLENISHMENT

HEATING	• STRIP HEAT BEND ZONES ONLY • ELECTRIC RESIST-ANCE WIRE HEATERS • MATERIAL CON-FIGURED FOR HIGH LONGITUDINAL AND LOW TRANS-VERSE HEAT TRANSFER	GREATEST EFFICIENCY OF ENERGY UTILIZATION
FORMING	PASSIVE ROLLERS (ROLLTRUSION)	• LOW DRAG MINIMIZES FORMING ENERGY • SHORT FORMING TRANSITION LENGTH FOR MINIMUM MACHINE LENGTH
COOLING	FLUID COOLED PLATENS	• MATERIAL COOLS TOO SLOWLY IN VACUUM • ENSURES UNIFORMITY AND STRAIGHTNESS OF FINISHED CAP
DRIVE	FRICTION ROLLERS	• DOES NOT DAMAGE MATERIAL OR COATING • COMPACT DRIVE UNIT MINIMIZES MACHINE LENGTH

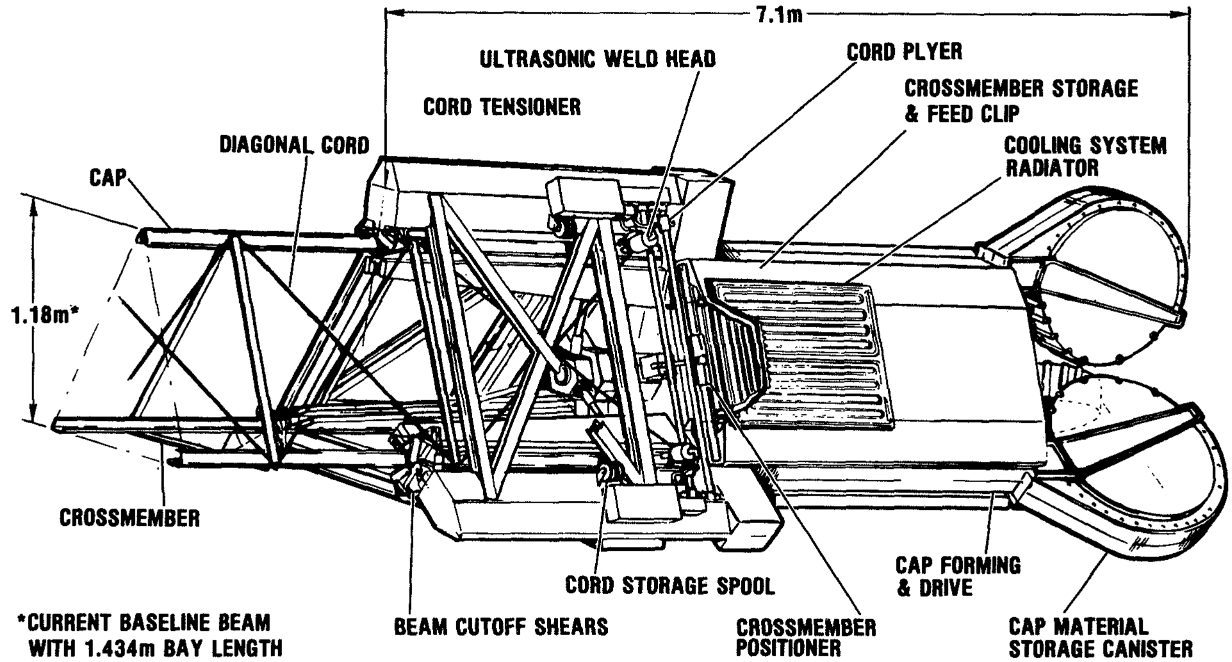


Figure 1. Beam builder concept.

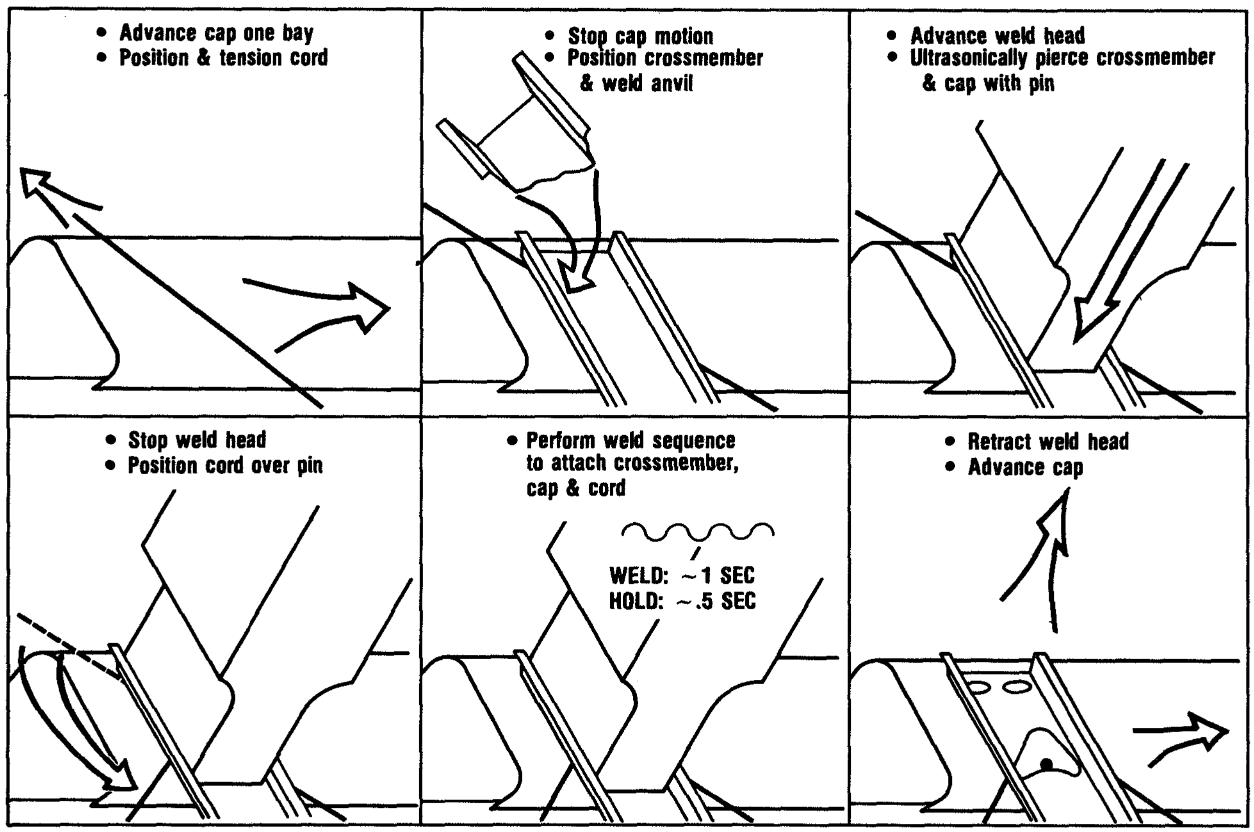


Figure 2. Beam assembly processes.

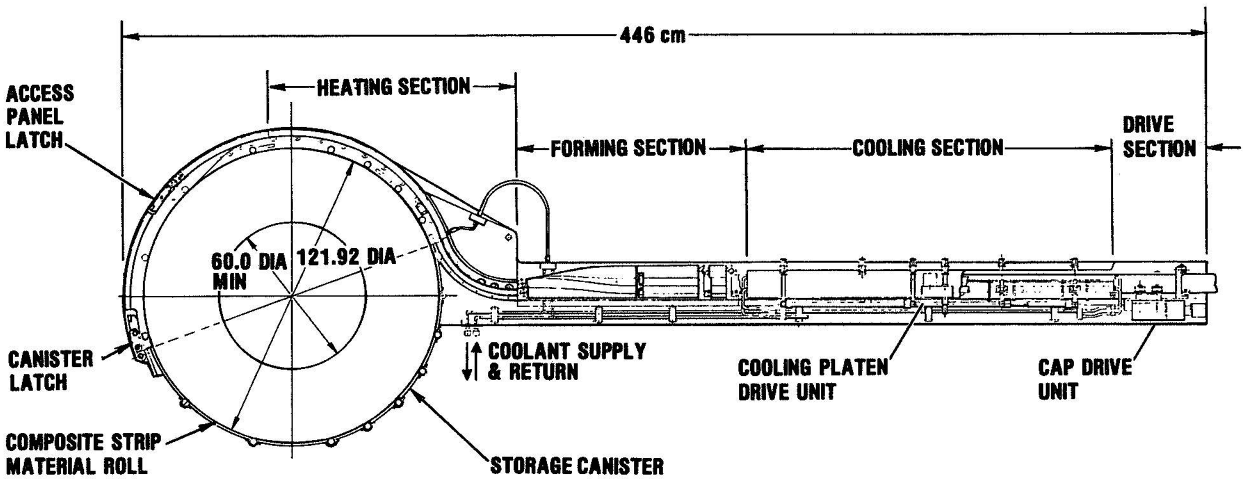
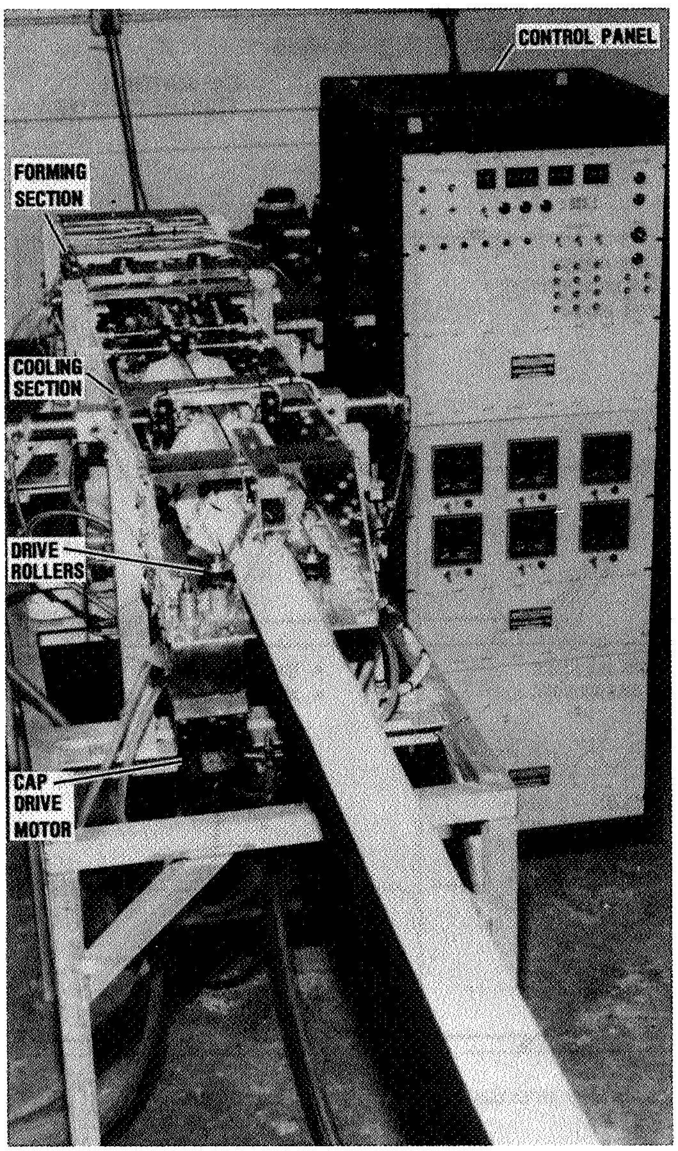


Figure 3. Beam builder cap forming machine design concept.



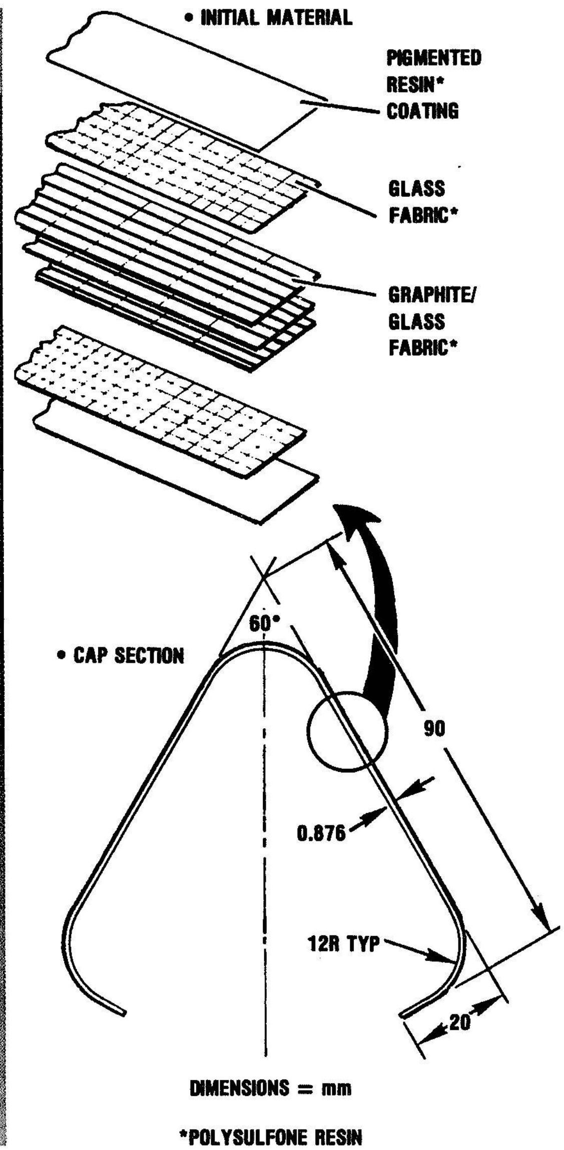


Figure 4. Prototype cap forming machine.

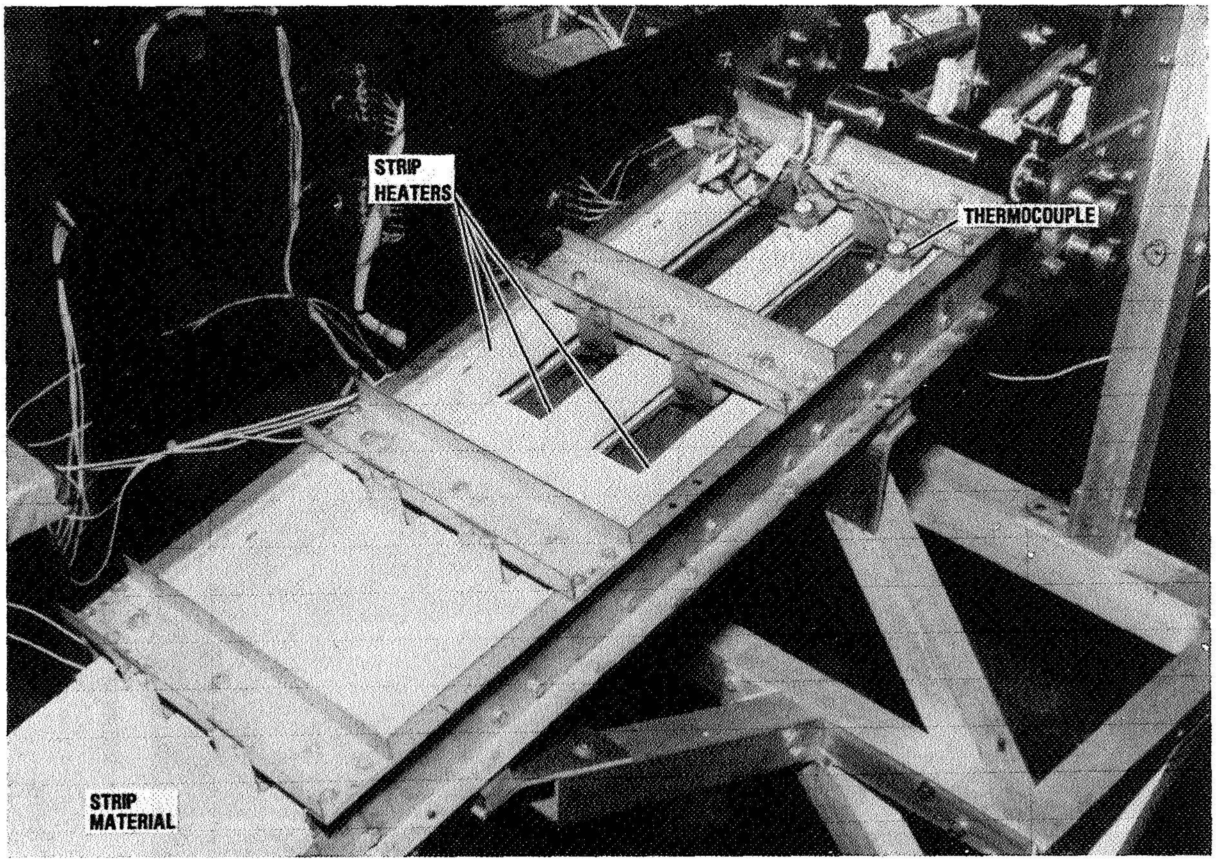


Figure 5. Cap forming machine heating section.

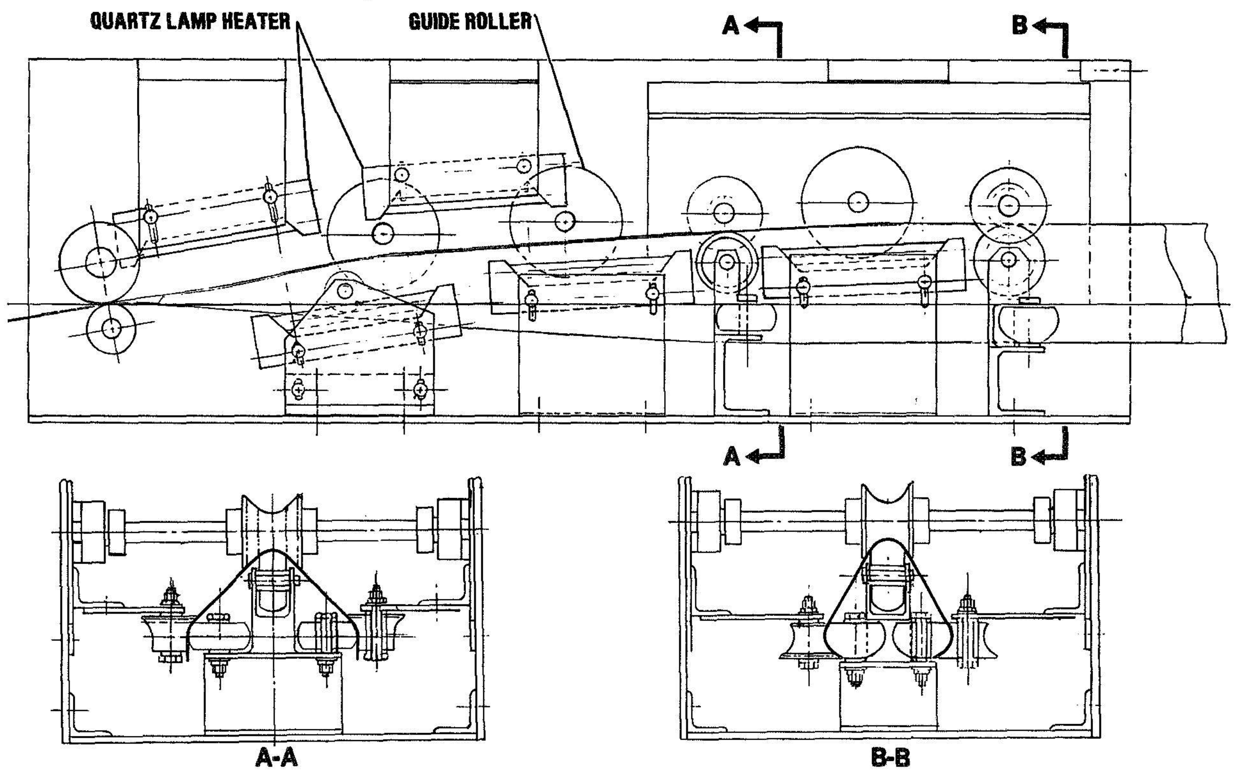
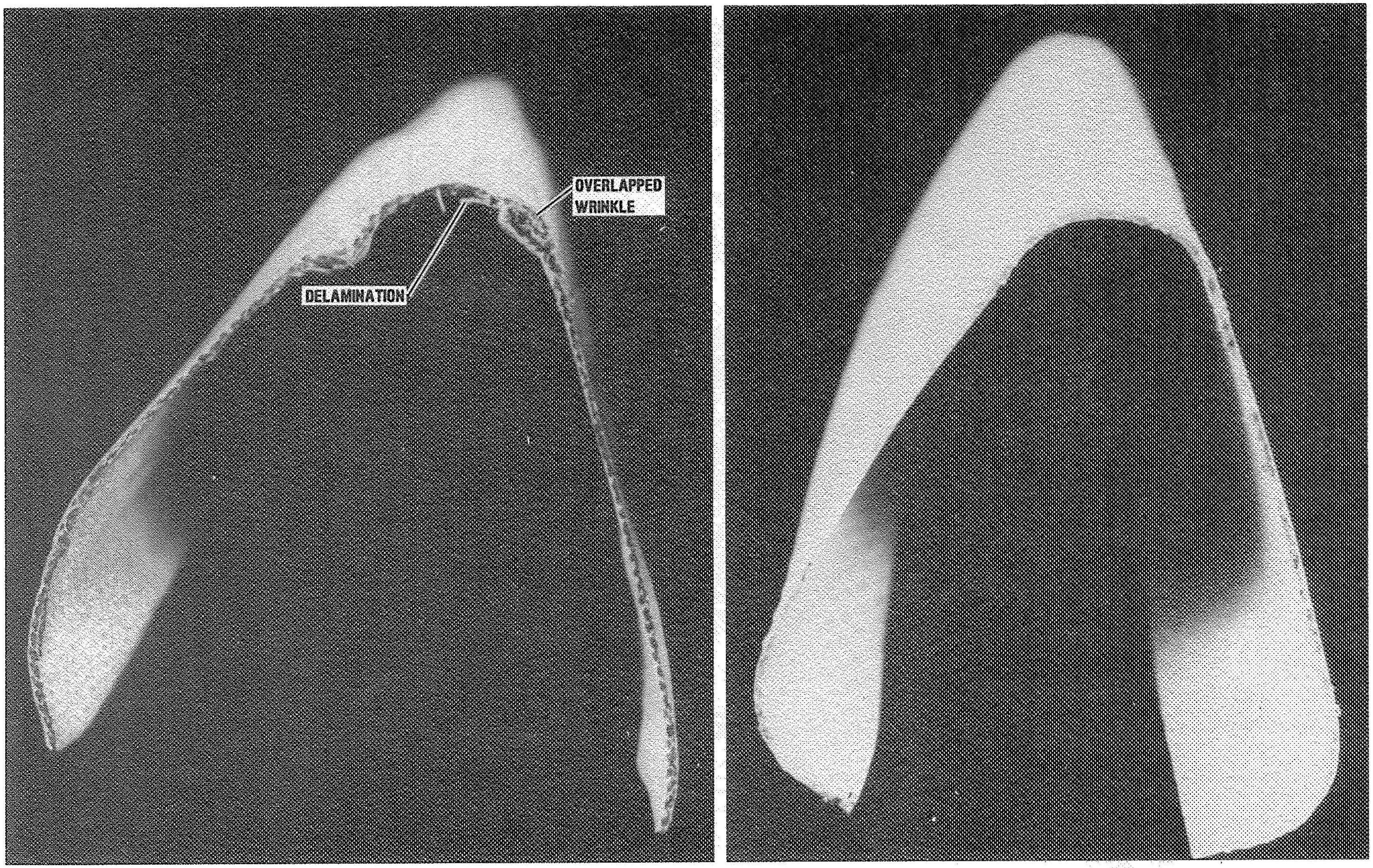


Figure 6. Initial forming section design.



• SECTION OF AN INITIAL FORMING TEST SPECIMEN

• SECTION OF INTERIM MATERIAL SPECIMEN FORMED WITH IMPROVED FORMING SECTION

Figure 7. Forming test specimens.

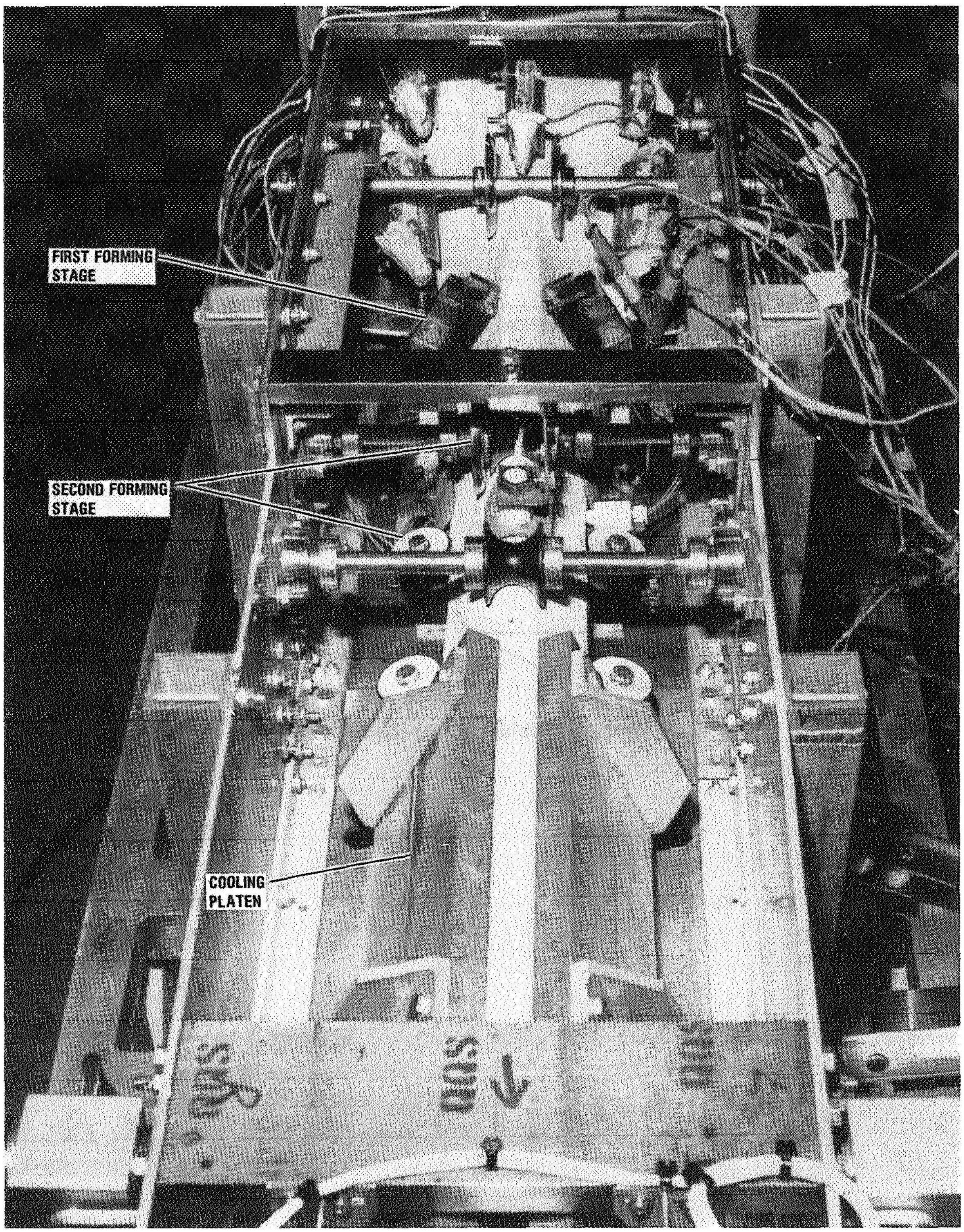


Figure 8. Improved forming section.

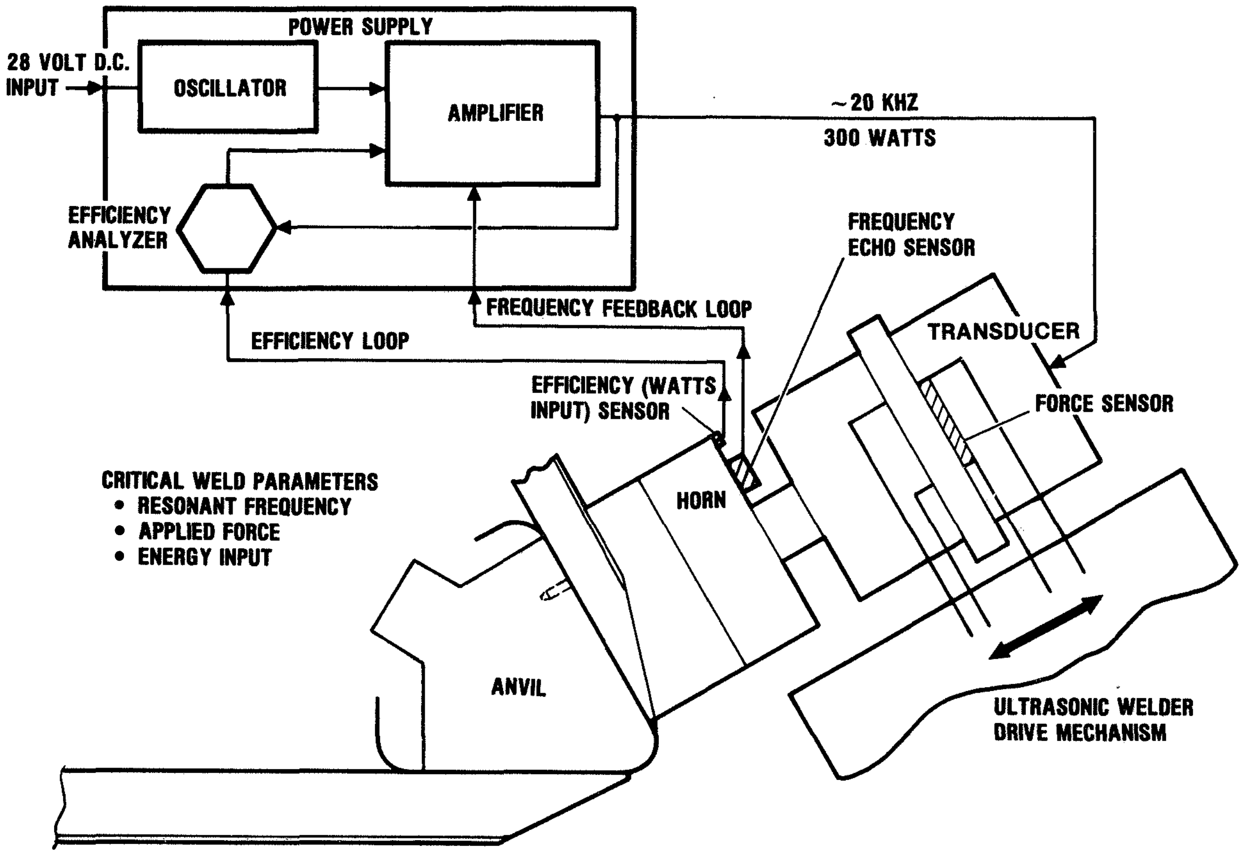


Figure 9. Ultrasonic welding process control techniques.