**PRELIMINARY STUDY OF HIGH
SPEED MACHINING**

By R. E. Jordan

Published July 1980

Milestone Report
D. S. Bartel, Project Leader

Project Team:
W. G. Cooper
A. W. Cunningham

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PRELIMINARY STUDY OF HIGH-SPEED MACHINING

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Prepared by R. E. Jordan

The feasibility of a high speed machining process has been established for application to Bendix aluminum products, based upon information gained through visits to existing high speed machining facilities and by the completion of a representative Bendix part using this process. The need for an experimental high speed machining capability at Bendix for further process evaluation is established.

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The Bendix Corporation
Kansas City Division
P. O. Box 1159
Kansas City, Missouri 64141

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SUMMARY

This project was initiated to investigate the advantages of high speed machining and to determine what benefits could be obtained from the application of this technology to the manufacture of aluminum products at Bendix Kansas City. After an initial review of the literature it was decided to further investigate the usefulness of this process by visiting several facilities that had high speed machining capabilities and by placing a purchase order to demonstrate the current state of technology. This limited production of a test configuration was to be compared with the same configuration produced at Bendix by conventional machining methods. Three high speed machining facilities were visited during the plant visit phase of the project: the Lockheed Missiles and Space Corporation in Sunnyvale, California, the Vought Corporation in Sterling Heights, Michigan, and the Convair Division of General Dynamics in San Diego, California.

Lockheed was visited first. They had initiated an investigation of high speed machining as part of an industrial process improvement program. Two machines were modified to support this project, a Sundstrand 5-axis Omnimill, Model OM-3 and a Bullard vertical turret lathe (VTL). These machines were fitted with high speed spindle systems to replace conventional spindles. Based on the success of these machine modifications, a third machine was purchased to support the high speed production of aluminum parts. This machine was an Ex-Cell-O Model 208, 4-axis, machining center designed specifically for high speed work. This machine has just recently been installed; therefore, it has had limited production application using the high speed processing techniques developed on the modified machines.

These techniques are very different from those commonly used for conventional machining. Conventional machining is defined as using everyday machine shop feeds and speeds. High speed machining involves combining shallow axial and heavy radial depths of cut with high feed rates to produce large metal removal rates at moderate chip loads. According to Lockheed, this method lowers tool forces, permits machining with little or no thermal distortion, and significantly reduces fabrication time while maintaining or improving part quality.

The Vought Corporation was the second facility visited. Vought conducted a study for the U. S. Army Research and Development Command to investigate the machining of aluminum alloys at speeds greater than those currently used in industry. Vought's choice of machines for modification to support this study was similar to Lockheed's. An OM-3 was modified almost identically to Lockheed's configuration. Vought also chose a VTL as a second machine, but this machine was modified by the addition of a high speed spindle on the side tool post to permit cutting at right angles to the

axis of table rotation. This configuration was to be used for gathering data on the process.

Vought experimented with different processing techniques and found conventional techniques to be best for their application. Vought was satisfied with the results of their investigation and concluded that the high speed machining of aluminum was a viable process. They felt, however, that more powerful machine tools with more rapid travel rates than are currently available are needed to obtain the full benefits of this process.

The Convair Division of General Dynamics was the last facility visited. Convair's main interest in high speed machining was directed toward the internal milling of cylindrical shells. They felt the small dimensions of the high speed spindle would be beneficial for this application. Experimental investigation of this process has been delayed by Convair until a spindle can be obtained that is more compatible with their needs.

Several important opinions concerning the high speed machining process were voiced at each of the facilities visited. Dynamic balancing of tool holders and spindles to less than 0.00002 inches in displacement was found to be essential for successful spindle operation. Very tight tolerances (± 0.0002) were placed on cutting tool geometry for the same reason. All feeds and speeds were determined by trial and error methods since sufficient data has not been obtained to develop dependable empirical cutting relationships. Safety shielding, usually in the form of polycarbonate resin cages, was required to control coolant overspray and to protect machine operators from broken tools or spindles, although such accidents appear to be rare. Finally, high speed cutting tool geometry must be very different from that used in conventional machining in order to provide adequate chip removal capability and to ensure proper cutter rigidity and tool life.

Lockheed was selected for the part production phase of the investigation. Lockheed was required to provide full information concerning tool forces, machine horsepower, tool geometry, and all machine programming required for part production. A concurrent effort was pursued at Bendix as a control to produce the same part configuration using only conventional machining techniques. This way it was possible to compare the part samples to establish what benefits were present in the high speed production process as well as to document what disadvantages, if any, were encountered.

Based on the test part comparisons and the information supplied by Lockheed, it was discovered that the Lockheed process produced the test parts in a significantly lower fabrication time of 215 minutes versus 330 minutes machining time and with a similar

part tolerance to the conventional method. The thin wall part sections were produced successfully without the additional support required for conventional parts. Tool wear was slight, but accurate tool life estimates could not be made. Surface finish was within that specified for the test configuration (125 rms).

Based on all the information gathered in this study, the high speed machining of aluminum does appear to be a feasible process. Conventional machines can be modified to operate in the high speed mode, and while the interrelationships of such parameters as feeds and speeds, tool geometry, tool forces, and programming techniques are not well understood, enough work has been done to establish a starting point for further investigation of this process. This investigation will involve the modification of a Bendix machine for use in high speed machining tests.

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DISCUSSION

SCOPE AND PURPOSE

High speed machining is a method of material cutting that combines high tool rotational velocity and rapid feed rates with shallow axial depths of cut to establish large material removal rates while maintaining or reducing tool chip loads. It is reported that this technology results in a significant reduction in both fabrication time and cutting tool forces while producing improved surface finishes and better dimensional control than is possible using conventional machining techniques.¹ These claims are based on a study of the high speed machining of aluminum by Lockheed Missiles and Space Corporation. The results of this investigation indicate that high speed machining technology has been developed to the point where it can be applied successfully to production aluminum machining applications.

This study was initiated to evaluate the publicized advantages and to determine whether the reported benefits could be advantageously applied to complex aluminum products at Bendix Kansas City. The study also sought to discover what disadvantages, if any, are inherent to this method of material removal and what effects these difficulties would have on Bendix applications.

This report discusses the evolution of this study, the evaluation of the study results, and the rationale for continuing the investigation of high speed machining for production application at this facility.

PRIOR WORK

Little quantitative scientific work has been directed toward understanding the theoretical aspects of high speed metal cutting. The pioneering work of Salomon on tool-chip interface temperatures,² the ballistic machining experiments of Vaughan,³ Arndt,⁴ and Morton and Woodward,⁵ and the theoretical investigations of Recht^{6,7} have been basically directed toward the ballistic or ultra-high speed cutting of metals and are not directly applicable to production machining speeds. These studies do, however, indicate machining at very high cutter velocities may be feasible for several materials.

The experimental investigations conducted by Colwell and Quackenbush,⁸ the Lockheed Corporation,⁹ the Vought Corporation,¹⁰ and the Convair Division of General Dynamics indicate high speed machining should be a profitable and realistic alternative to conventional machining methods once the controlling parameters

are better understood. The studies conducted by the three companies were directed toward developing a manufacturing capability and, therefore, there was little discussion of the basic metal removing mechanisms of the process. They do, however, provide excellent initial experimental parameters such as feeds and speeds, tool geometry, and tool chip loads which should prove useful in a supplemental investigation of the process.

With the exception of the work of Colwell and Quackenbush, these experimental studies were limited to the investigation of the high speed machining of aluminum alloys. While these studies definitely support the feasibility of aluminum cutting, it is unknown if these results can be extended to the cutting of other materials. Colwell and Quackenbush's work on high speed titanium machining shows that it is possible to machine this material at very high speeds under laboratory conditions. Unfortunately, the results of this work also indicate the high speed machining of titanium alloys will not have practical applications until dramatic advances are made in cutting tool material technology.

Several theories have been presented to explain the cutting mechanisms involved in high speed machining. These include adiabatic shear,³ changes in fracture mode,¹¹ internal workpiece vibration,⁸ and surface melting-friction reduction mechanisms.⁵ No definitive theory has yet emerged, however, because of the limited experimental work done to date and the complexity of the phenomena.

ACTIVITY

After reviewing the articles appearing in the literature, it was decided to pursue a two-phase initial investigation of high speed machining technology. The first phase of this approach involved visiting the existing high speed machining facilities, tool vendors, and high speed spindle or machine tool manufacturers. These visits were undertaken to examine the processes and tooling involved, to determine what modifications were necessary to convert an existing machine, and to obtain preliminary knowledge of what part configurations were most suitable for this process.

The second phase of the project involved placing an order with one of the facilities to produce a limited number of a Bendix designed test configuration. This approach was chosen for comparison with an identical configuration produced by conventional techniques at Bendix.

Work Performed by Lockheed

The first high speed test facility visited was the Lockheed Missiles and Space Corporation, Sunnyvale, California. Lockheed undertook

an investigation of high speed machining as part of an industrial engineering process improvement program. Based on the earlier reports of ballistic machining research, it was felt significant reductions in machining time could be realized by operating numerically controlled (NC) machines at much higher feeds and speeds than are conventionally used. Two NC machines were selected to support the project, since manually controlled machine tools could not be operated effectively at the speeds anticipated to be encountered in the study.

The first machine to be modified was a Sundstrand 5-axis, Model OM-3 mill (Figure 1). The modification consisted of removing the conventional high speed spindle and replacing the spindle support housing with a similar housing bored to accept any one of three high speed spindles. These spindles were rated at 18,000, 30,000, and 100,000 rpm (1885, 3142, and 10,472 rad/s) maximum and were designed and manufactured for high speed operation by the Bryant Grinder Corporation, a division of the Ex-Cell-O Corporation. The first two spindles were limited to 1.000 in. (25.4 mm) maximum tool diameter. The last spindle could accept a 0.250 in. (6.35 mm) maximum tool diameter. All spindles were lubricated using an oil-air mist system. Spindle rpm was controlled manually. Spindle temperature and vibration were constantly monitored by an automatic machine shutdown system in order to prevent inadvertent spindle damage from excessive heat buildup or accidental spindle impact caused by programming errors. The entire spindle system was subjected to a vibration study in order to ascertain what spindle speeds were most suitable for optimum operation. No other modifications were performed on this machine. The chief disadvantage of this modification was that the machine's automatic tool change capabilities could not be utilized because of the Bryant spindle configuration. The geometry and materials used for the cutting tools on this machine, as well as the feeds and speeds used in testing, are discussed later in this report.

The second Lockheed machine modified was a Bullard vertical turret lathe (Figure 2). This machine was modified to include a table capable of turning 600 rpm (62 rad/s) and a 30 horsepower (22,371 watts), 6000 rpm (628 rad/s) ram milling head (Bryant spindle). This machine was designed to accept cutters up to 8.00 inches (203 mm) in diameter. Bendix personnel observed this machine cutting with a three tooth, 6.50 in. (165 mm) tool removing a reported 50 in.³/min (819 cm³/min) on an aluminum workpiece. This setup was used only on open ended parts to simplify rapid chip removal.

Based on the results of the OM-3 testing, Lockheed ordered a special Ex-Cell-O, Model 208, 4-axis, NC milling center. The spindle on this machine was capable of 18,000 rpm at 30 horsepower and the maximum table feed rate was 300 in./min (7630 mm/min). The

Figure 1. Sunstrand OM-3 Mill, Modified by Lockheed Corporation

machining center was equipped with a pallet shuttle, an automatic tool changer, special safety shielding, and special shutdown instrumentation. The tool holders used were a double retention Ex-Cell-O design. This machine has been used for limited production of one Lockheed part.

Method of Processing Used by Lockheed

Lockheed has adopted a unique method of processing for their high speed applications. This method may be most simply described as making many cutting passes at shallow axial depths of cut at very rapid table feed while taking a heavy radial depth of cut (roughly

Figure 2. Bullard Vertical Turret Lathe
With Bryant Spindle and Control
Consoles

two-thirds cutter diameter). This approach (Figure 3) differs from the conventional method of cutting at or near full axial depth in one pass using correspondingly lighter radial cutter depths and slower table feeds. The Lockheed method seems to significantly reduce cutter forces and part deflection. This method of processing is not new and the reduction in cutter forces has long been recognized.¹² However, this process was not practical until both high rpm milling spindles and NC machines with accurate and rapid table travel capabilities were developed. Both of these capabilities must exist in order to control the tool-chip load acting on the cutter. As a result of this processing method, thin wall production capabilities are enhanced since this method leaves as much stock as possible both in front of and below the cutter. Conventional methods progressively cut the entire wall thinner and thinner. This leaves little material remaining to resist cutter forces. As a result, successful, conventionally produced thin walls sometimes require use of potting techniques to support the wall until the machining operation is complete.

Lockheed's processing practices do produce a visually unusual machined surface as compared to conventionally produced ones.

CONVENTIONAL MACHINING

HIGH SPEED MACHINING

Figure 3. High Speed Machining

(Refer to surface finish solution.) The shallow axial depth passes made many times on a wall cause the part to show tool marks clearly and appear to cause the part to have a somewhat rougher surface finish than is actually present. It is not known if this effect can be eliminated or controlled using different tool geometry.

Lockheed Work

The term ultra-high speed machining often appears in connection with the Lockheed work. Ultra-high-speed machining is a term most closely associated with the ballistic experiments of Vaughn and Arndt; it describes cutting at speeds of 1000 or more feet per second. Lockheed's current work would be more correctly titled high-speed machining which implies cutter speeds higher than those commonly used to cut a given material.

Much of the work conducted by Lockheed has been reported in the literature.^{1,8,10,13,14} It seems appropriate to outline the conclusions regarding this process that appear in these articles:

- Operating feeds and speeds up to two orders of magnitude greater than those used in conventional machining;
- Overall machine performance improvements of 50 percent;
- Metal removal rates of 8 to 10 in.³/min/horsepower at 30,000 rpm (3141 rad/s) spindle speeds to control the already low cutting tool forces through proper selection of feeds, speeds, and cutter depths;
- A very high percentage of the heat generated in cutting is absorbed and carried away by the resulting chips;
- Workpiece and cutting tool thermal distortion problems do not occur;
- Workpiece and cutting tools remain cool during high speed cutting;
- The only limitations on increasing feeds and speeds indefinitely are the responses and vibration characteristics of the machine tools;
- High speed machining can be used successfully to machine pockets 2.750 in. deep (70 mm) with interconnecting webs of 0.040 in. thickness (1 mm) using no wall support and an "as machined" surface roughness of 25 to 60 RMS;

- It should be possible to remove 100 in.³/min (2540 mm/min) using 20 horsepower (19 kW), 20,000 rpm (2094 rad/s) spindle; and
- Cutting speeds in the ballistic machining range may eventually be reached.

This increase in metal removing efficiency is thought to be caused by a change in the work material's mode of fracture. That is a transition from ductile tearing to brittle fracture.

It is felt that high speed metal cutting is a process applicable to all materials and Lockheed has indicated a strong interest in titanium.

Work Performed by Vought Corporation

The second high-speed machining facility visited was the Vought Corporation in Sterling Heights, Michigan. Vought conducted a study for the U. S. Army Missile Research and Development Command. The scope of this study included the development of manufacturing methods and technology for the machining of aluminum alloys at significantly higher speeds than are currently used and to demonstrate that the methods developed were both practical and cost effective when compared to current machining practices.

Vought's machine modifications were very similar to those employed by Lockheed. As with Lockheed, a OM-3 (similar to Figure 1) and a Bullard VTL (Figure 4) were chosen for modification. Spindle selection and spindle placement were different, however. Vought chose to use a Bryant spindle rated at 20,000 rpm for their OM-3 modification. A standard Ekstrom-Carlson routing spindle was mounted perpendicular to the axis of table rotation on the side tool post of the VTL. This modification permitted cutting perpendicular to a rotating part. This spindle operated at three different nominal rpm settings: 14,400, 7200, and 3600 rpm (1508, 754, and 377 rad/s). Only the highest setting was used during the cutting investigations on this machine tool. These modifications are completely described in Vought's final report.¹⁰

Method of Processing Used by Vought

In contrast to the work performed by Lockheed, Vought chose to examine high speed machining using more conventional processing techniques for their OM-3 tests. Cutting experiments were conducted in which axial depths of cut were varied from 0.125 in. (3.175 mm) to a maximum of 2.00 in. (50.80 mm). The corresponding radial depths of cut varied from 2.00 in. (50.80 mm) to less than 0.100 in. (2.54 mm). In effect, the experimental cutting parameters varied from completely conventional to parameters approximating those used by Lockheed. Similar parameters were also used

Figure 4. Bullard VTL, Modified by Vought Corporation

on the VTL experiments. Vought used the data generated in these studies to develop empirical relationships between depth of cut (both axial and radial) and spindle horsepower.

Vought also investigated tool geometry, tool material, and the feasibility of high speed drilling during their study. Final tool geometry was very similar to that used by Lockheed. Both solid carbide and high speed steel tools were used and both were found satisfactory except for deep pocket or abrasive alloy (7075 AL castings) milling, where carbide proved to be more satisfactory. High speed drilling tests were performed using conventional high speed tool steel drills (0.25 in. diameter). Drilling feed rates up to 100 in./min (2540 mm/min) were used at 20,000 rpm. All tool indexing during these experiments was done at the maximum table travel rate of 200 in./min (5080 mm/min).

Claims by Vought

Because of the large volume of work, tentative results, and conclusions appearing in the final Vought report, it would be impractical to discuss each point in detail. Therefore, the information is briefly summarized in the following listing:

- Aluminum may be machined at high speed because of its low melting point.
- There does not appear to be any limit to the theoretical speeds at which aluminum can be machined.
- Spindle rotational velocities in excess of 40,000 rpm (4189 rad/s) would be required to produce the most economical cutting speeds.
- Tool life in aluminum increases for chip loads up to 0.008 to 0.014 in. (0.2 to 0.36 mm) depending on the alloy of interest.
- Until table speeds can be increased to above 400 in./min (10 m/min) higher rpm spindles are not needed. Also, rotary table speeds must be increased for optimum cutting conditions to exist.
- More powerful spindles are required to machine effectively using larger tools.
- More positive spindle stops are needed.
- Cutters over 1.0 in. (25.4 mm) in diameter require dynamic balancing for successful operation.
- Cutting fluids are generally recommended.
- High speed steel drills are adequate for high speed drilling in aluminum.
- High speed machining is a sound, viable process.
- Machine tools can be beneficially retrofitted with high speed spindles.
- Automatic tool change capabilities must be developed for optimum machine tool use.

Work Performed by General Dynamics

The Convair Division of General Dynamics was the last high speed facility visited. Convair's main thrust in this area has been directed toward investigating the internal milling of cylindrical

shells. They have modified a Turchan numerically controlled horizontal lathe to accept a high speed spindle mounted perpendicularly on an 8 in. diameter (203 mm) boring bar. A Stanley 8-horsepower (6 kw), single speed, 20,000 rpm (2094 rad/s) router head was used initially as the high speed spindle. Convair's future plans in this area included purchasing a Bryant spindle and performing similar modifications on three more machines for production use.

Convair chose this machine modification approach in order to more easily fit the spindle inside the cylindrical shells and to perform internal milling work. Little experimental work was done except for a limited number of straight line cuts in order to determine acceptable feeds and speeds. High speed steel tools are used, again with a geometry similar to Lockheed's. It was thought carbide tools might be used for more difficult work if it was encountered. Tool vibration was controlled by designing and fabricating cutting tools with minimum dimensional variation (0.0002 TIR). Dynamic balancing techniques were also used on large tools (2 in. diameter) and the tool holders. Feed rates have been raised to as high as 400 in./min (10.2 m/min) but tapes are usually programmed at 300 in./min (7.6 m/min) and ran at 50 percent of this value. More extensive experimental work on feeds, speeds, and tool configurations have been delayed until another spindle with a longer bearing life is obtained.

According to Convair, they have developed their capabilities to the point of successfully producing nine different cylindrical part configurations.

Rationale for Lockheed Order

After a complete review of the literature it was decided that the most effective way to evaluate the claims made for high speed machining would be to place a purchase order to demonstrate the state of technology of a representative Bendix design. The Lockheed facility was selected for this phase of the program. An identical effort was pursued at Bendix to produce the same part configuration using conventional machining techniques. As a result of these efforts, it was possible to directly compare the two part samples in order to establish what benefits were present in the high speed production process, as well as to document any disadvantages.

The specific intent of this order was to examine the following advantages cited by Lockheed for high speed machining as compared to conventional methods:

- Increased productivity by reduced cycle time,
- Enhanced thin wall capability,
- Improved surface finish,
- Extended tool life,
- Reduced cutter forces,
- Reduced burrs,
- Reduced noise,
- Improved spindle horsepower utilization, and
- Milling in an increasing spiral to produce a round hole.

Other considerations important to the evaluation of this technology for possible Bendix application were also investigated in this study. These included dimensional tolerance capabilities, NC part programming difficulties, and machine tool dynamic behavior.

The preceding factors were incorporated into the test program in three ways. First, many of these factors were directly examined by design inherent in the test configuration. Due to the importance of this design it will be detailed in the following section. Second, Lockheed was required to provide full information concerning tool forces, machine horsepower, tool geometry, and all machine programming including automatic programmed tool information and post processor listings required for part production. Lockheed also supplied both new and used cutting tools, a time study of the complete machining operation, and a study of the spindle vibration characteristics used to determine optimum spindle rotational velocities. Finally, it was required that Bendix personnel observe the machining of at least one complete part in order to evaluate the machining process first hand.

The conventional part production effort was undertaken concurrently with the Lockheed order. These parts were produced with the objective of being truly representative of standard production capabilities. Off-the-shelf cutters and existing tooling were used. Part tapes were optimized using regular procedures. No instrumentation was used and no attempt was made to artificially reduce cycle time by using methods not commonly practiced in normal production.

Test Part-Design Intent

The selection of a part configuration, as stated earlier, was a critical element in the successful evaluation of the Lockheed technology. The following list was used to select an optimum part for the evaluation of the factors listed in the previous section.

- The configuration should be easily tooled, programmed, and inspected.
- It should be representative of Bendix production requirements.
- It must require the removal of significant volumes of material.
- Machining must involve both two and three dimensional milling.
- The configuration should test machine dynamics.
- The part should meet or exceed the claimed machining capabilities of Lockheed.

No standard Bendix production part completely satisfied all these selection criteria. Therefore, the test configuration shown in Figure 5 was designed. This design incorporated several features which required full utilization of the listed test capabilities as outlined in the following listing and shown in Figure 5.

- The large hole (F) was used to check spiral milling capabilities.
- Pockets B, C, D, and E required large stock removal and tested deep pocket capabilities.
- The 3- and 10-degree slopes required disproportionate movement between machine axes to evaluate machine dynamic characteristics.
- Corner radii shown in the top of the part check curve blending capabilities.
- Small corner radii around Pocket F forced complete machine motion reversal.
- Pockets C, D, and E tested thin wall production capabilities. The outside wall along pocket E required 0.020 in. thick (0.51 mm) wall.
- Tolerances of ± 0.003 in. (0.076 mm) tested dimensional capabilities.

Figure 5. Configuration of Test Part

- 6061-T651 aluminum alloy was chosen for part material due to its wide use at Bendix.
- Pocket C required three axes of simultaneous motion.

Method of Processing Lockheed Order

The method of processing used by Lockheed to produce the test part configuration was similar to the processing methods reported in the Lockheed articles 1, 8, 10, 13, 14. Examination of the post processor listings indicated a total machining time of 199.9 minutes for the 10 tapes used to produce this configuration. Total tape

footage was 4,028 feet (1229 m). The actual cutting parameters used for part generation are summarized below.

All parts were rough machined using a 0.750 in. (19.05 mm) diameter, two fluted, solid carbide, end mill (Figure 6) rotating at 24,000 rpm (2513 rad/s). Axial depth of cut was 0.200 in. (5.08 mm), radial depth of cut was 0.500 in. (12.70 mm), and the feed rate was 120 in./min (3048 mm/min). These parameters produced a metal removal rate of 10.6 in.³/min (174,000 mm³/min).

Finish machining was performed using an identically dimensioned but longer shanked, 0.750 in. diameter, end mill (Figure 7). Spindle speed and radial depth of cut were unchanged for this operation, but the axial cutter depth was reduced to 0.100 in. (2.54 mm) and the feed rate was also reduced to 80 in./min (2032 mm/min). These changes reduced the material removal rate to 4.0 in.³/min (65,500 mm³/min) for this process.

The three dimensional pocket was machined using a two-fluted, 0.750 in. diameter, solid carbide ball end mill (Figure 8) also rotating at 24,000 rpm. Axial and radial depths of cut remained unchanged from the finish operation described previously. The feed rate for this sequence was programmed at 80 in./min (2032 mm/min) but was overridden during part production to 50 percent of this value. The removal rate for this phase of production was 2.0 in.³/min (32,800 mm³/min.).

Finally, the 0.125 in. (3.175 mm) corner radii were generated using a 0.250 in. (6.35 mm) diameter solid carbide end mill rotating at 30,000 rpm (Figure 9). Axial depth of cut was 0.030 in. (0.762 mm) with a nominal radial depth of cut of 0.165 in. (4.19 mm). The removal rate in this instance was 0.01 in.³/min (163.87 mm³/min).

The cutting tools described previously were a Lockheed design especially developed for high speed machining application.

Three significant differences existed in the cutting tools utilized for this program as compared to conventional aluminum cutting end mills. These differences occur in the land clearance angles, the flute lengths, and the helix angles. The rationale for these design changes was empirically developed at Lockheed and optimized on an iterative basis during earlier high speed machining tests conducted at that facility. The final configurations used for the production tooling are described in the following paragraph.

Primary and secondary circumferential land clearance angles were specified as 12 degrees 30 minutes and 18 degrees 20 minutes, respectively, and represent an increase by approximately 30 percent over that used on conventional end mills. The increased clearance angles are required in order to prevent heeling which would be

LOCKHEED MISSILES & SPACE
J. W. CARROLL ORGN/86-32
31 JAN 78

SHANK & FLUTE O.D.
.0002 T.I.R. MAX.
HELIX ANGLE 26°

NOTE: TOOL WILL BE RUN AT
20.00 RPM. FLUTES MUST BE SYM.

Figure 6. High Speed Roughing End Mill

LOCKHEED MISSILES & SPACE
J. W. CARROLL ORGN/86-32
31 JAN 78

SHANK & FLUTE O.D.
.0002 T.I.R. MAX.
HELIX ANGLE 26°

NOTE: TOOL WILL BE RUN AT
20.00 RPM. FLUTES MUST BE SYN.

Figure 7. High Speed Finishing End Mill

LOCKHEED MISSILES & SPACE
J. W. CARRQLL ORGN/86-78
31 MARCH 78

SHANK & FLUTE O.D.
.0002 T.I.R. MAX.
HELIX ANGLE 26°

NOTE: TOOL WILL BE RUN AT
20.00 RPM. FLUTES MUST BE SYM.

Figure 8. High Speed Ball End Mill

LOCKHEED MISSILES & SPACE
J. W. CARROLL ORGN/86-32
31 JAN 78

SHANK & FLUTE O.D.
.0002 T.I.R. MAX.
HELIX ANGLE 26°

NOTE: TOOL WILL BE RUN AT
20.00 RPM, FLUTES MUST BE SYN.

THIS VIEW IS ENLARGED
NO SCALE

Figure 9. High Speed End Mill, 0.025 Inch Diameter

experienced using conventional clearance angles at the higher feed rates. (Small diameter end mills require greater angles than large diameter end mills.) Flute lengths were specified to be one diameter of an end mill. Experience has indicated that at feed rates of 80 to 120 in./min (2032 to 3048 mm/min), short flute lengths are preferable during deep pocket milling since the resultant increased length of full shank diameter offers a greater resistance to deflection. The longer flute lengths are not required at the relatively shallow cuts of 0.100 to 0.200 in. depth (2.54 to 5.08 mm), which is typical for high-speed deep pocket milling. Furthermore, the shorter flute lengths require less grinding which provides an economic savings. A helix angle of 26 degrees was specified in lieu of a conventional 30 degree angle. Previous experience has borne out that the more generous gullet radius generated by the 26 degree helix angle reduces chip build up in the flute and gullet areas.

Part Comparison of Lockheed Order

The six parts produced for Bendix evaluation by Lockheed were received in May 1978. (Figures 10 and 11 show a representative Lockheed produced part.) The five control parts manufactured at Bendix were completed a few weeks later. Lockheed's final report on the project, copies of the data taken on tool forces and spindle horsepower, and the cutting tools purchased by Lockheed to support the project were also received at this time. Numerical control data and tape listings were received earlier by Bendix personnel during a visit to Lockheed to observe the actual machining sequences. Notes made by Lockheed personnel during production were also provided.

Material samples removed from the Lockheed raw material part blocks prior to machining were examined in order to ensure that the material used in the experiments was 6061 aluminum alloy. This was accomplished by performing a chemical analysis on the samples. The results of this analysis appear in Table 1 and indicate that the raw material examined was indeed 6061. Hardness measurements taken on the samples also confirm this conclusion. Microstructure photographs taken of the samples (Figures 12, 13, and 14) are supportive of the fact that this material had received a T651 heat treatment since the grains present in the alloy were elongated in the longitudinal direction.

The photomicrographs also indicate an ASTM grain size of 5. This information was obtained in the hope that it might be later correlated with tool force and horsepower data, and similar additional data taken on other aluminum alloys and used to establish empirical cutting relations describing high speed metal removal behavior. Unfortunately, this correlation was not possible and is explained in the following section.

Figure 10. Diametric View of Test Part

Figure 11. Perspective View of Test Part

Table 1. Chemical Analysis in Weight/Percent of Material Used in the Study

Sample Number	Element				Hardness (R _B)
	Magnesium	Copper	Silicon	Cobalt	
L1	0.98	0.31	0.57	0.13	57
L2	0.97	0.32	0.58	0.14	58
L3	0.96	0.32	0.58	0.13	60
L4	0.99	0.32	0.58	0.13	58
L5	0.97	0.32	0.59	0.14	57
L6	0.97	0.33	0.60	0.13	58
L7	0.97	0.32	0.58	0.13	57
L8	0.97	0.32	0.58	0.13	57
B1	0.98	0.32	0.59	0.13	57
B2	0.97	0.32	0.59	0.13	59
B3	0.97	0.32	0.58	0.13	57

Force and Horsepower Measurements of Lockheed Order

The instrumentation used to monitor, collect, and record the machine horsepower and tool forces generated during machining is listed in Table 2. Samples of the graphs obtained from this procedure are shown in Figures 15 and 16. Unfortunately, the usefulness of this information is questionable when considering the nature and the frequency of the forces generated during the machining of the test parts. If the assumption is made that a cutting force is generated each time a tooth of the milling cutter strikes the workpiece, it is possible to calculate the frequency of this force in the following manner.

$$\text{Frequency} = \frac{\text{spindle rpm}}{60 \text{ secs/min}} \times \text{number of teeth/cutter}$$

If one considers a two toothed cutter rotating at 24,000 rpm (typical parameters for Lockheed processing), this frequency is approximately equal to:

$$\frac{24,000}{60} \times 2 = 800 \text{ cuts/sec } 800 \text{ Hz}$$

Figure 12. Transverse Microstructure of 6061-T651 Material Before Machining (100X)

Figure 13. Longitudinal Microstructure of 6061-T651 Material Before Machining (100X)

Figure 14. Longitudinal Microstructure of
6061-T651 Material Before
Machining, Reduced Magnification (50X)

Thus, even though the variations in cutter force amplitude and duration are not known, the fundamental frequency of the force is. This frequency is too high to be accurately monitored using the Lebow dynamometer. This force measuring device also has a rated nonlinearity, hysteresis and repeatability of ± 0.15 percent full scale, which corresponds to a maximum force resolution of ± 4.50 lbs (Table 3). Many of the forces reported by Lockheed are below or near this figure. Finally, all the measured quantities were recorded using a Hewlett Packard 7044A pen recorder. While the maximum measurable input frequency for this device could not be documented, it is doubtful that it even approaches the 800 Hz value. Considering these facts, it is assumed that the force graphs presented by Lockheed represent some type of time average force measurement. Since the exact nature of these data could not be determined, correlation into empirical cutting relationships was not attempted. Fortunately, since horsepower is usually a time averaged measurement, the data provided for spindle horsepower should give an accurate indication of the average horsepower required to machine using high speed parameters. This data is presented in Appendix F.

Figure 15. Plot of Power Versus Time

Dimensional Inspection of Lockheed Order

All Bendix and Lockheed produced parts were subjected to a complete dimensional inspection using a Bendix Sheffield Cordax 3000 measuring machine. 866 points on the bottom, sides, and corner radii of the part were examined. The sides and radii were measured at four different levels along the 3 in. (76.2 mm) part height. The lower right hand corner of the part was used as an origin for these measurements. Each point was compared to the nominal point dimensions calculated using a print of the part configuration, and any difference from nominal was recorded as a deviation. This information was segregated into separate data sets which described each pocket in terms of bottom, walls, and radii deviations. This was done to determine which method of processing was superior for each pocket section. These data sets were examined by performing a statistical analysis and by compiling the range of deviations for each section.

Figure 16. Three Plots of Force Versus Time

Figure 16 Continued. Three Plots of Force Versus Time

Table 2. Instrumentation Used by Lockheed

Instrument	Model	Manufacturer	Accuracy (Percent)
Three-Axis Dynamometer	6423	Lebow Associates	0.15, non-linearity 1 cross-talk
Strain Gage Amplifier	9178	Daytronic Corporation	0.1, full scale
Accelerometer	2213E	Endevco*	5, maximum transverse
Charge Amplifier	2725	Endevco	± 1.5 , full scale gain
X-Y-Y Plotter	7046A	H-P**	± 0.75 , full scale
Spectrum Analyzer	1510	EMR	± 1 frequency
Profilometer	3	Micrometrical	± 1 microinch
X-Y-Z Plotter	7044A	H-P	± 0.75 , full scale
Signal Conditioner	9005	Daytronic Corporation	0.1, full scale

*Dynamic Instrument, Division of Becton-Dickinson and Company

**Hewlett-Packard Company

A summary of the statistical data appears in Appendix G, Tables G-1 and G-2 where the mean deviation, the standard deviation about this mean, and the number of inspection points used to calculate these values are recorded. This data is further summarized for each group of parts in Table G-3. Based on this summary, the conventional parts produced by Bendix may be considered slightly closer to print than the parts produced by Lockheed. An examination of the range of deviation for each part and part section appears in Tables G-4 and G-5. This data is summarized in Table 4. Based on this summary, the Bendix parts show a range which is equal to or narrower than the Lockheed parts in almost every case.

These results must be tempered by several factors. Both sample lots show large part-to-part variation. This wide scatter between parts in a given group makes it difficult to show a significant difference between the two groups. Due to the small number of parts in each group, no effort was made to use cutter compensation or machine offsets to make small changes in part geometry to improve final part dimensions. One final factor which must be considered is the age of the machine tools used to produce the parts in question. The Moduline used for Bendix production is a

Table 3. Grinding/Milling Dynamometer Specifications

Specification*	Tolerance
Nonlinearity of rated output	±0.15 Percent
Hysteresis of rated output	±0.15 Percent
Repeatability of rated output	±0.15 Percent
Zero balance of rated output	±2 Percent
Bridge resistance, ohms normal	350 or 700 ohms
Temperature compensated (range)	+30 to +150
Temperature range, usable	65 to 200
Temperature effect on output of reading	±0.01 Percent
Temperature effect on zero of rated output	±0.01 Percent
Overload rating, safe; of rated output	±0.50 Percent
Excitation voltage, maximum	20 Vac or dc
Insulation resistance, bridge/case	1000 megohms at 50 Vdc
Crosstalk	1 component loaded, 1 component unloaded in 2 percent of rated capacity

*Capacity X 3000 lbs
Y 3000 lbs
Z 3000 lbs
Stiffness 1×10^6 lbs/inch

Table 4. Range of Measured Deviation About Nominal Dimension

Pocket	Section	Conventionally Machined Part Deviation		High Speed Machining Part Deviation	
A	Bottom	+0.0032	-0.0053	+0.0042	-0.0107
A	Walls	+0.0067	-0.0057	+0.0118	-0.0128
A	Radii	+0.0025	-0.0129	+0.0014	-0.0101
B	Bottom	-0.0010	-0.0042	+0.0062	-0.0100
B	Walls	+0.0227	-0.0110	+0.0130	-0.0169
B	Radii	+0.0064	-0.0103	+0.0191	-0.0206
C	Bottom	+0.0091	-0.0028	+0.0046	-0.0080
C	Walls	+0.0088	-0.0059	+0.0083	-0.0158
C	Radii	+0.0038	-0.0078	+0.0183	-0.0262
D	Bottom	+0.0079	-0.0022	+0.0070	-0.0101
D	Walls	+0.0211	-0.0121	+0.0072	-0.0156
D	Radii	+0.0078	-0.0050	+0.0157	-0.0137
E	Bottom	-0.0015	-0.0041	+0.0009	-0.0105
E	Walls	+0.0164	-0.0081	+0.0204	-0.0149
E	Radii	+0.0078	-0.0119	+0.0249	-0.0135
F	Bottom	+0.0160	+0.0044	+0.0026	-0.0207
F	Radii	+0.0082	-0.0037	+0.0117	-0.0135

relatively new machine and has been in use approximately 2 years. The OM-3 used by Lockheed has been used in production for over 10 years. Looseness and wear on the Lockheed machine could account for differences in tolerances held on the part.

Combining the inspection results with the consideration of the factors mentioned, it may be assumed no drastic difference in part tolerances exists between the two part production processes. This conclusion, however, should be subjected to further investigation in future high speed machining studies to check its validity.

Surface Finish of Lockheed Order

The test configuration chosen for this study was specified to have an as-machined surface finish not greater than 125 μ in. Both Bendix and Lockheed samples had measured surface finishes in this range; however, the Lockheed parts had finishes which measured 25 to 60 μ in. rms, but which appeared rougher than these values. This discrepancy was at first attributed to the instrument used to measure the surface. However, when the surfaces were rechecked using a different machine,

similar results were obtained. The discrepancy was finally traced to the method used to determine the measured value. This measurement is an average, taken over some discrete distance along the part surface, of the peak to peak asperity height along this distance. In the original measurements this averaging distance was 0.031 in. A typical surface trace at this setting is shown in Figure 17. Over this short distance the small steps on the part are shown in Figure 18 and are effectively ignored by the averaging process. When a special longer averaging path of 3.0 in. (76.2 mm) was selected, the surface roughness increased to values of 100 to 150 μ in. rms (Figure 19). It may be concluded that the shorter distance (standard method) setting measures the surface finish between the marks or steps left by this processing method and the longer distance measures an average or gross surface finish across the part. It was thought that Lockheed uses the first method described for finishes in the 25 μ in. range, but this cannot be established without examining the finish used by Lockheed. All Bendix and Lockheed parts contained areas with rougher surfaces than those discussed above; however, these rougher areas were usually caused by chatter marks and only nominal part areas were examined to obtain an average value of the finish on each part.

Figures 20 and 21 show representative photomicrographs of the thin wall surface structure of the Bendix and Lockheed parts respectively. As indicated by the photographs, the high speed machined displays a more irregular structure than is present on the conventionally machined parts. Measurements of the peak to valley asperity height range from approximately 0.0003 in. (0.007 mm) for the Bendix part to 0.0006 in. (0.015 mm) for the high speed machined part. Figures 22 and 23 show individual asperities on the high speed machined part.

Lockheed Order - Time Study

Since a significant reduction in part fabrication time was one of the principal advantages cited for high speed machining as compared to conventional techniques, a study was made of the time required to produce the test configuration for each method. Examination of the machine tapes revealed a total computer tape cycle time for the ten Lockheed tapes of 199.9 minutes and 302.1 minutes for the three Bendix tapes. Based on these figures, the theoretical time required for conventional machining could be reduced approximately 34 percent by switching to high speed machining techniques.

The actual machining time for the Lockheed process appears in Table 5. As indicated, the actual time needed to produce the test part on the modified OM-3 is 277.3 minutes. This figure includes all manual tool changes. If one assumed this machine had an automatic tool change capability, this time could have been reduced to 214.7 minutes. This assumption may be considered reasonable since new high speed machining centers, such as Lockheed's new Ex-Cell-O 208 described earlier, do have this capability.

Figure 17. Surface Finish of Lockheed Part, 0.030 Inch Length of Trace

Figure 18. Typical Appearance of Part Surface

Figure 19. Surface Finish of Lockheed Part Taken Over 2.75 Inches

Figure 20. Bendix Produced Thin Wall Surface Structure (100X)

Figure 21. Lockheed Produced Thin Wall Surface Structure (100X)

Figure 22. Magnified Cross Section of Lockheed Asperity (500X)

Figure 23. Additional Cross Section of Lockheed Part Asperity (500X)

Table 5. Time Study on Bendix Part

(Configuration A, Tool No. C-9318 Drawing)

	Norm Min A	Norm Min B
Load, Unload Part	4.44	4.44
*Chg. Cutter Holder	13.71	
Chg. Cutter (Hand)	4.13	2.20
Indicate Cutters	12.73	
Change Tapes	18.57	
*Touch Off W/5" Feeler	9.92	
Blow Off Chips	4.43	1.00
Machine Time	193.38	193.38
Change Tape	2.31	2.31
Touch Off 5" Feeler	2.36	
Machine Time	11.33	11.33
	277.31	214.66
	$\div 60 = 4.62 \text{ hrs}$	$\div 60 = 3.58 \text{ hrs}$

*Includes two men.

NOTE: No set-up time involved in this time study.

1. Tape No. 4a finish was not used on this time study as the part was considered scrapped at the end of sequence No. 630. Sequence No. 650 requires the same time to machine as No. 630. The time for loading the tape and performing sequence No. 630 was added to the total time study and shown as items 9, 10, and 11 on the time study summary.
2. Column A on the time study summary is the actual hours required to fabricate the part. All delays not normally occurring, such as taking of movies and extra inspections, have been eliminated.
3. Column B is the actual hours if the hand loading of cutters, touch off with feeler gage, and indicating of cutters was eliminated. Also, if larger cutters were used and depth of cuts increased on the rough machining operations, an estimated savings of 45 minutes could be realized.

A similar study of the Bendix production process yielded an actual machining time of 330.0 minutes. This figure does not include the time required to pot the part cavities between the roughing and finishing operations. This potting was required to provide additional support for the thin wall sections during conventional machining operations. Based on these figures (214.7 minutes versus 330.0 minutes), the time required to machine the test piece could be reduced 35 percent by switching from the conventional method to a high speed process.

Tool Inspection of Lockheed Order

The tool geometry required to machine aluminum in the high speed mode is very different from the standard tool geometry used for the conventional machining of this material. These changes in geometry are required by several factors occurring in the high speed process. For example, at very high rotational velocities the physical removal of the generated chips becomes a problem unless the helix angle is reduced to increase chip acceleration directly away from the tool workpiece interface. Short flute lengths are required to minimize both tool and workpiece vibrations which tend to be excited by the high frequency force oscillations which may cause premature cutter wear. Long flutes may also adversely affect surface finish due to chatter if not controlled. This phenomenon also explains the superiority of carbide tools in the area of thin wall production, since carbide has a significantly greater elastic modulus compared to high speed tool steel cutter materials. The reduced tool diameter above the flutes (Figures 7, 8, and 9) is required to ensure that the cutting tools do not contact the workpiece above the actual cutting area, while traversing the part on the many passes required by this processing method. The extremely tight tolerances placed on the cutter dimensions are necessitated by the high spindle velocities which makes dynamic tool stability a critical factor for successful operation. These tolerances reduce the necessity of dynamic tool balancing, which can be a time consuming operation.

The nominal tool geometries used in the generation of the test configurations appeared in an earlier section of this report. In addition, these tools were completely inspected by Lockheed after delivery to ensure proper dimensions. These inspection reports appear in Table 6. The unused tools delivered to Bendix at the conclusion of this order were also inspected there. The results of this inspection appear in Table 7. The results of both inspections were similar and no important variations were noted. The tools used in actual part production were also examined by Lockheed after use. The results of this inspection appear in Table 8. Photographs of selected tools both before and after use appear in Figures 24 through 27. These photographs indicate very little absolute tool wear; however, the length of time each tool was used was not documented and accurate tool life measurements could not

Table 6. Tool Inspection Summary

Cutter Characteristic	Tool No.						Should Be
	1	2	3	4	1*	2*	
Shank Diameter	0.5000	0.4999	0.4999	0.5000	0.5000	0.5000	0.500 $\begin{smallmatrix} +0.0000 \\ -0.0002 \end{smallmatrix}$
Shank Length	1.878	1.875	1.876	1.879	1.178	1.198	4 at 17/8 2 at 1.200
Flat	0.120	0.120	0.135	0.125	1/8	1/8	1/8 x shank length
Necked Area Diameter	0.228	0.228	0.227	2.265	2.275	0.228	0.230 $\begin{smallmatrix} +0.000 \\ -0.005 \end{smallmatrix}$
Necked Area Length	0.870	0.870	0.870	0.870	1.550	1.550	4 at 0.870 2 at 1.550
Helix	26°	26°	26°	26°	26°	26°	26°
Flute Diameter	0.2409	0.2405	0.2403	0.2405	0.2403	0.2405	0.240 $\begin{smallmatrix} +0.001 \\ -0.000 \end{smallmatrix}$
Flute Length	0.300	0.300	0.310	0.300	0.310	0.300	0.25
Web	0.135	0.122	0.134	0.134	0.151	0.135	53% (0.132)
Check	0.174	0.163	0.172	0.178	0.205	0.175	72% (0.180)
Raised Land	NA	NA	NA	NA	NA	NA	NA
Rake	11°	11°	11°	11°	11°	11°	11° ± 10
Primary	19°	19°	14°	14°	16°	14°	12° 30'
Secondary	23°	23°	21°	20°	21°	20°	18° to 20°
Total Indicator Reading	0.0000	0.0001	0.0002	0.0002	0.0002	0.0000	0.0002 max

* Not used.

Table 6 Continued. Tool Inspection Summary

Cutter Characteristic	Tool No.						Should Be
	1	2	3	4	5	6	
Shank Diameter	Acceptable						0.750 ^{+0.0000} -0.0002
Shank Length	2.0"	2.0"	2.0"	2.0"	2.0"	2.0"	2.0
Flat	Size and Location Acceptable						1/2 x 45°
Necked Area Diameter	0.7185	0.7185	0.7185	0.7190	0.7185	0.7185	0.720 ^{+0.000} -0.005
Necked Area Length	2.230	2.230	2.230	2.250	2.230	2.230	2 1/4
Helix	Acceptable						26°
Flute Diameter	0.7504	0.7506	0.7509	0.7505	0.7505	0.7494	0.750 ^{+0.001} -0.000
Flute Length	0.760	0.770	0.780	0.770	0.740	0.780	0.75
Web	0.400	0.398	0.399	0.401	0.400	0.397	53% (0.397)
Check	0.555	0.550	0.555	0.550	0.552	0.548	72% (0.540)
Raised Land	0.091	0.101	0.100	0.102	0.100	0.095	13% (0.097)
Rake	10°	11°	11°	10° 30'	10°	10°	11° ±10
Primary	14°	13° 30'	13° 30'	13°	14°	14°	12° 30'
Secondary	20°	20°	20°	20°	20°	20°	18° to 20°
Total Indicator Reading	0.0000	0.0000	0.0001	0.0002	0.0000	0.0001	0.0002 max

Table 6 Continued. Tool Inspection Summary

Cutter Characteristic	Tool No.						Should Be
	1	2	3	4	5	6	
Shank Diameter	0.7498	0.7498	0.7497	0.7498	0.7498	0.7498	0.750 ^{+0.0000} -0.0002
Shank Length	2.015	2.000	2.000	1.980	2.000	2.010	2.0
Flat	45° in 2 places 0.492						45° in 2 places 0.500
Necked Area Diameter	0.715	0.718	0.717	0.717	0.716	0.717	0.720 ^{+0.000} -0.005
Necked Area Length	1.210	1.210	1.225	1.235	1.215	1.210	1 1/4"
Helix	26°	26°	26°	26°	26°	26°	26°
Flute Diameter	0.7506	0.7500	0.7509	0.7495	0.7505	0.7505	0.750 ^{+0.001} -0.000
Flute Length	0.770	0.750	0.750	0.750	0.750	0.750	0.75
Web	Acceptable						53% (0.397)
Check	Acceptable						72% (0.540)
Raised Land	0.085	0.080	0.095	0.090	0.095	0.090	13% (0.097)
Rake	11°	11°	11°	11°	11°	11°	11° ±10
Primary	12° 30'	13° 30'	13° 20'	13° 30'	13° 30'	13°	12° 30'
Secondary	19°	19°	19°	19°	19°	18°	18° to 20°
Total Indicator Reading	0.00015	0.0002	0.0002	0.0000	0.0002	0.0002	0.0002 max

Table 7. Bendix Test Inspection Summary

Item	Tool Number Dimensions*						
	8670-1 Tool 1	8670-1 Tool 2	8670-2 Tool 1	8670-2 Tool 2	8670-3 Tool 1	8670-3 Tool 2	8670-4 Tool 1
A	0.2404	0.2400	0.7505	0.7408	0.7490	0.7500	0.7485
B	20/64	20/64	52/64	50/64	0.8000	0.7500	0.7625
C	3-2/64	3-2/64	4-2/64	4.000	5.0200	5.0000	5.0000
D	0.2282	0.2272	0.7172	0.7174	0.7184	0.7192	0.7187
E	2-56/64	2-56/64	2.000	2-1/64	2.000	2.0000	2.0050
F	0.5000	0.5000	0.7500	0.7500	0.7500	0.7498	0.7500
G	12°	12°	15°	15°	12°	18°	12°
H	22°	22°	23° 30'	24°	23°	23°	21°
J	1/64	1/64	0.0250	0.2000	0.0220	0.0160	0.0200
K	0.1800	0.1850	0.6000	0.5820	0.6300	0.6150	0.5500
L	25°	28°	25°	25°	25°	25°	25°
M	10	10	6 30	6 30	7	7	8
N	20°	20°	18°	18°	18°	18°	17°
Concentricity	0.0002	0.0001	0.00005	0.00005	0.0001	0.0001	0.0001
Finish	8✓	8✓	24✓	16✓	16✓	8✓	16✓

*All linear dimensions are in inches. One inch equals 25.4 millimeters.

Dimensions are shown to nearest 1/64 for B, C, E, J, and K.

0.0001 for A, F, and Concentricity.

0.001 for D.

1 for G, H, L, M, and N.

Table 8. Lockheed Inspection of Tool Wear Measurements

Tool No.	Flute Diameter		Raised Land Width		Length	C-9318 PNs Machined *	Visible Wear
	Before	After	Before	After			
8670-1-1	0.2409	0.240	NA	0.0425	0.300	1 through 7	0.007" wear at tip
8670-1-3	0.2403	0.240	NA	-	0.310	8	None
8670-2-4	0.7495	0.7495	0.090	0.090	0.750	1, 4, 7	Flute corner rounded slightly
8670-2-5	0.7505	0.750	0.095	0.091	0.200***	6, 8	None
8670-2-6	0.7505	0.750	0.090	0.087	0.750	1, 2, 3	None
8670-3-1	0.7504	0.750	0.091	0.091	0.760	3	0.001" deep chip- corners rounded
8670-3-2	0.7506	0.750	0.101	0.097	0.770	1, 2	0.002" dia. round on corners
8670-3-3	0.750	0.750	0.110	0.095	0.200***	4	Flute corner chipped
8670-3-4	0.7505	0.750	0.102	0.093	0.770 CB	-	Shank abraded
8670-3-5	0.7505	0.750	0.100	0.0975	0.200***	4, 5, 6, 7, 8	None
8670-3-6	0.7494	0.749	0.095	0.094	0.780 CB	4	0.001" deep chip
8670-4-1	0.7485	0.7485	0.098	0.098	0.770	6, 7, 8	None
8670-4-2	0.751**	0.751	0.102	0.098	0.770	1, 2, 3, 4, 5	None

*PNs indicate that order of manufacture.

**Represents dimension after resharpening

***Flute length was reduced to improve surface finish.

be made. This problem was complicated by the unique wear mechanisms exhibited by carbide materials which tend to wear more unevenly and erratically than conventional steel tools. Further high speed machining studies should address this question more fully in order to determine exactly what effect this processing method has on tool life.

Safety Considerations

Based on information gathered at the facilities visited during the course of this investigation, the use of the high speed machining process does not pose any unreasonable risks to either employees or equipment. The present machine tools used are basically conventional in nature except for the spindle modifications indicated earlier. Operational noise levels were comparable or lower than those encountered in conventional machining. Coolants are common water soluble oils. Mist and overspray must be controlled by shielding or proper ventilation. Fragmentation of spindles, cutting tools, and parts was a potential hazard due to the high rotational velocities used in the process. This risk was minimized at all facilities through the use of polycarbonate sheet shielding which also served to control coolant splash and overspray. Fire hazards appear to be minimal with wet machining and

Figure 24. New Lockheed Tool, End View

Figure 25. New Lockheed Tool, Side View

Figure 26. Used Lockheed Tool, End View

Figure 27. Used Lockheed Tool, Side View

control methods which are consistent with present Bendix practices. Dry machining operations could present fire, safety, and health concerns, but these concerns are not a factor for aluminum alloys since production operations will be run with coolant. Dry machining of other alloys such as titanium, however, could present a much greater risk.

ACCOMPLISHMENTS

Several significant accomplishments were realized as a direct result of the facility visits and the completion of the test part order which occurred during this phase of the high speed machine process development order. All personnel involved gained a better general understanding of the high speed processing method, the cutting and machine tools required to utilize this method, and the rationale used in part selection and numerical control programming. Initial cutting parameters including feeds, speeds, tool geometry, and depths of cut, were obtained which will greatly accelerate evaluation of the process in future investigations. Detailed information was gathered which will simplify both machine tool selection and modification for high speed use. Conversations with other investigators in this area clarified many questions which could not have been easily answered in any other way. These included such concerns as safety and health considerations, processing techniques, and process limitations. The importance of dynamic balancing for tools, tool holders, and spindles was established as a primary concern for successful process implementation. Based on the information gathered during this extensive study, high speed machining techniques as applied to aluminum alloys could result in reduced part machining time without significant corresponding reductions in part quality. However, more work is needed to completely understand and fully evaluate this process for general manufacturing use. Areas of further investigation include accurate measurement of the forces present at the tool-work piece interface, establishment of empirical machining relationships, and the optimization of tool geometry and programming techniques in order to refine the process for general Bendix production applicability.

FUTURE WORK

The feasibility of the high speed machining process for general production application has been well established by the results of both this investigation and those cited in the references. The actual applicability of the method, however, requires further investigation to establish what benefits can be obtained and what costs will be incurred in attaining these benefits as compared to the conventional practices now in use. Gathering this information requires further testing and study. Therefore, the next phase of

the project will involve the modification of a Sundstrand OM-3. This 5-axis mill will be fitted with a high speed spindle system and will be used to generate data for further evaluation of the process. This machine will be instrumented so that tool forces, machine vibrations, and other process parameters can be monitored and recorded for use in evaluating the process for production use and to establish a data base for the development of experimental relationships to describe the process.

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Appendix A

SPINDLE VIBRATION ANALYSIS

Machine tool vibration is an important consideration in high speed machining because of the high rotational velocities encountered using this processing method. In order to successfully apply this technology it is necessary to select operating speeds so that spindle and machine tool vibrations are minimized. This is most easily accomplished by avoiding spindle rotational speeds which excite machine tool resonance speeds. In these regions, the large magnitude oscillations caused by the resonance vibration phenomena result in poor part quality and unacceptable tool and spindle force variations. These variations reduce tool life and enhance the possibility of catastrophic spindle failure.

The selection of the optimum spindle operating region may be determined by performing a vibration analysis on the spindle in question. This analysis requires mounting an accelerometer on the spindle housing to monitor spindle vibration and using the output of this transducer to drive a spectrum analyzer. This device records spindle vibration in terms of frequency and magnitude (Figure A-1). By gathering this information over the entire operating range it is possible to generate a plot of vibration magnitude and frequency versus spindle speed as shown in Figure A-2. As indicated on Figure A-2 the spindle analyzed should operate with a minimum of vibration in the region of 17,000 rpm (1780 rad/s) while maximum spindle vibration occurs between 7000 and 13,000 rpm (733 and 1361 rad/s) indicating this region should be avoided. Figure A-2 is known as a spindle signature. This signature gives an accurate picture of the vibrational characteristics of this spindle under the tested loading conditions, but these results cannot be extended to other similar spindles nor will they apply to this spindle if it is rebuilt or otherwise modified.

Figure A-1. Frequency and Magnitude of Spindle Vibration

Figure A-2. Spindle Signature

Appendix B

SUMMARY OF PRELIMINARY LOCKHEED NUMERICAL CONTROL TAPES FOR BENDIX TEST PART CONFIGURATION

TAPE 1, FIRST ROUGHING TAPE

1. Rough 3.750 inch (95.25 mm) diameter pocket at 40 inches/minute (1016 mm/minute) using spiral cut to depth of 1.90 inches (48.26 mm), leaving 0.500 inch (12.7 mm) on side. (Two passes)
2. Go to inspection point - N020 - PROGRAM STOP
3. Rough pocket one at 120 inches/minute (3048 mm/minute) to a depth of 1.90 inches (48.26 mm), leaving 0.125 inch (3.175 mm) per side. Cut ramps 0.100 inch (2.54 mm) one way - returns to clean up. (19 passes)
4. Go to inspection point - N030 - PROGRAM STOP
5. Rough pocket two to depth of 1.900 inches (48.26 mm) at 120 inches/minute (3048 mm/minute). Roughs inside first then contours, leaving 0.500 inch (12.7 mm) per side. (19 passes) Ramps 0.100 inch (2.54 mm) in all directions.
6. Go to inspection point - N040 - PROGRAM STOP
7. Rough pocket three to depth of 1.200 inches (30.48 mm) at 80 inches/minute (2032 mm/minute). Feed cutter down 0.100 inch (2.54 mm) at start of each cut. (12 passes)
8. Go to inspection point - N050 - PROGRAM STOP
9. Rough right side to a depth of 1.800 inches (45.72 mm) at 120 inches/minute (3048 mm/minute). Ramp cut 0.100 inch (2.54 mm) each direction. (9 passes)
10. Go to inspection point - N060 - PROGRAM STOP
11. Rough top side to a depth of 1.800 inches (45.72 mm) at 120 inches/minute (3048 mm/minute). Ramp cut 0.100 inch (2.54 mm) each direction. (9 passes)
12. Go to inspection point - N070 - PROGRAM STOP
13. Rough outer right side and top contours at 120 inches/minute (3048 mm/minute) to a depth of 1.800 inches (45.72 mm). (18 passes) each 0.100 inch (2.54 mm) deep.

14. Go to inspection point - N080 - PROGRAM STOP
 15. Rough both sides of pocket five - right side at 80 inches/minute (2032 mm/minute) to depth of 1.800 inches (45.72 mm) 18 passes. Left side at 120 inches/minute (3048 mm/minute) to a depth of 1.900 inches (48.26 mm) - 19 passes.
 16. Go to inspection point - N090 - PROGRAM STOP
 17. Rough 2.875 inches (70.025 mm) radius at 40 inches/minute (1016 mm/minute) to a depth of 1.800 inches (45.72 mm) - Ramps 0.100 inch (2.54 mm) each direction. (9 passes)
 18. Go to inspection point - N100 - PROGRAM STOP
 19. Rough pocket four to a depth of 1.900 inches (48.26 mm) at 120 inches/minute (3048 mm/minute), leaving 0.0340 inch (8.636 mm) per side. (19 passes)
 20. Go to part load position
- TOTAL TAPE TIME: 52.1 minutes

TAPE 2, FINAL ROUGHING TAPE

1. Rough 3.750 inches (95.25 mm) diameter through at 40 inches/minute (1046 mm/minute), leaving 0.500 inch (12.7 mm) on side.
2. Go to inspection point - N220 - PROGRAM STOP
3. Rough pocket one at 120 inches/minute (3048 mm/minute), leaving 0.075 inch (1.905 mm) on bottom and 0.125 inch (3.175 mm) on sides. (11 passes)
4. Go to inspection point - N230 - PROGRAM STOP
5. Rough pocket two at 120 inches/minute (3048 mm/minute), leaving 0.075 inch (1.905 mm) on bottom and 0.500 inch (12.7 mm) on sides. (11 passes)
6. Go to inspection point - N250 - PROGRAM STOP
7. Rough right side at 120 inches/minute (3048 mm/minute), leaving 0.050 inch (1.270 mm) on bottom and 0.500 inch (12.7 mm) on sides. (5 passes)
8. Go to inspection point - N260 - PROGRAM STOP
9. Begin roughing of top at 120 inches/minute (3048 mm/minute), leaving 0.050 inch (1.27 mm) on bottom. (5 passes)

10. Go to inspection point - N270 - PROGRAM STOP
11. Complete roughing of top at 120 inches/minute (3048 mm/minute), leaving 0.050 inches (1.27 mm) on bottom. (11 passes)
12. Go to inspection point - N280 - PROGRAM STOP
13. Rough right side of pocket five at 80 inches/minute (2032 mm/minute), leaving 0.050 inch (1.27 mm) on bottom. (11 passes) Rough left side of pocket five, same feed rate. (10 passes)
14. Go to inspection point - N290 - PROGRAM STOP
15. Rough 2.875 inches (70.025 mm) diameter at 40 inches/minute (1016 mm/minute), leaving 0.050 inch (1.27 mm) on bottom and 0.120 inch (3.048 mm) on sides.
16. Go to inspection point - N300 - PROGRAM STOP
17. Rough pocket four at 120 inches/minute (3048 mm/minute), leaving 0.100 inch (2.54 mm) on bottom and 0.345 inch (8.763 mm) per side. (7 passes)
18. Go to part load position.

TOTAL TAPE TIME: 29.41 minutes

TAPES 3 AND 4, FINISH POCKETS 1, 2, 3 AND 5

1. Finish pocket one at 80 inches/minute (2032 mm/minute). Ramp out one way 0.100 inch (2.54 mm) deep. (28 passes)
2. Go to inspection point - N320 - PROGRAM STOP
3. Finish pocket two contour at 120 inches/minute (3048 mm/minute), 0.100 inch (2.54 mm) depth of cut per pass. (28 passes) One pass at finish depth. Finish middle of pocket two at 80 inches/minute (2032 mm/minute). (1 pass)
4. Go to inspection point - N330 - PROGRAM STOP
5. Finish pocket three contour at 80 inches/minute (2032 mm/minute), same depth as three. (12 passes) One final pass at depth of 0.050 inch (1.27 mm). Finish inside of pocket in one pass using APT pocket routine.
6. Go to inspection point - N340 - PROGRAM STOP

7. Finish pocket five contour at 80 inches/minute (2032 mm/minute), 27 passes at 0.100 inch (2.54 mm) depth per pass. Two passes at final depth. Finish pocket middle to depth at 80 inches (2032 mm) per minute.
8. Clear part to load position.

TOTAL TAPE TIME: 29.6 minutes

TAPES 5 AND 6, FINISH 3.750 INCH DIAMETER HOLE

1. Finish 3.750 inches (95.25 mm) diameter hole at 40 inches/minute (1016 mm/minute) using a generated helix cut. The circle is broken into arcs of 4 degrees with the cutter ramping down a depth of 0.00055 inch (0.0127 mm) every 4 degrees. Sixty-two circular passes are required. This process is broken by the Post Processor into two tapes. Subsequent tape iterations may double depth feed to reduce tape length and cycle time.
2. Go to load position.

TOTAL TAPE TIME: 15.65 minutes

TAPES 7 AND 8, FINISH PERIMETER

1. Finish outer right rim and top rim in one pass at finish depth. 27 passes at 0.100 inch (2.54 mm) depth of cut around the perimeter. All cuts are programmed at 80 inches (2032 mm) per minute.

NOTE: The cutter depth movement is a plunge before cutter contacts workpiece.

2. Go to load position.

TOTAL TAPE TIME: 23.08 minutes

TAPES 9 AND 10, FINISH POCKET 4 AND 0.125 INCH RADII

1. Finish pocket contour using ball end mill at 80 inches/minute (2032 mm/minute) using 0.100 inch (2.54 mm) depth of cut. (25 passes) Two passes at finish depth.
2. Go to inspection point - N620 - PROGRAM STOP
3. Finish bottom of pocket four - one pass at 120 inches/minute (3048 mm/minute).

4. Go to inspection point - N630 - PROGRAM STOP
5. Change to 0.250 inch (6.35 mm) diameter end mill.
6. Finish (4) places 0.125 inch (3.175 mm) radii at 20 inches/minute (508 mm/minute). Depth increment 0.030 inch (0.762 mm). (34 passes) Total depth 1.02 inches (25.908 mm).
7. Finish (2) places 0.125 inch (3.175 mm) radii at 20 inches/minute (508 mm/minute). Depth increment 0.030 inch (0.762 mm). (41 passes). Total depth 1.200 inches (30.48 mm).
8. Go to load position.

TOTAL TAPE TIME: 31.40 minutes

TOTAL TAPE TIME FOR COMPLETE OPERATION: 181.26 minutes

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Appendix C

LOADING AND OPERATING INSTRUCTIONS

LOADING INSTRUCTIONS

1. Load knee
2. Load backup plate
3. Load part using four bolts and then load tape Number 1 rough
4. Set block delete switch to OFF
5. Cycle to indicate
6. Cycle to hand load tool Number 2
7. Cycle to go to part load position (all tapes the same)
8. Turn block delete switch to ON
9. Cycle to go to touch off position

OPERATING INSTRUCTIONS

<u>Sequence Number</u>	<u>Operation</u>	<u>Tool Number</u>
	All touch off use 5.000 feeler	
010	Touch off Machine 3.750 bore (rough) 1.800 deep	8670-2
020	Touch off Rough narrow pocket 1.800 deep	8670-2
030	Touch off Rough bottom pocket	8670-2
040	Touch off Rough top left hand pocket 1.200 deep	8670-2
050	Touch off Rough right hand side 1.8 deep	8670-2

<u>Sequence Number</u>	<u>Operation</u>	<u>Tool Number</u>
060	Touch off Rough top 1.8 deep	8670-2
070	Touch off Rough profile top 1.8 deep	8670-2
080	Touch off Rough top pocket 1.8 deep	8670-2
090	Touch off Rough outer diameter of 3.750 diameter	8670-2
100	Touch off Rough center right hand pocket with 10 degree angle Part load position Load tool Number 3 Load tape Number 2 rough Block delete switch on	8670-2 8670-3
210	Touch off Rough 3.750 bore through	8670-3
220	Touch off Rough 3.750 bore through	8670-3
230	Touch off Rough bottom pocket	8670-3
250	Touch off Rough right hand side	8670-3
260	Touch off Rough top	8670-3
270	Touch off Profile top	8670-3
280	Touch off Rough top pocket	8670-3
290	Touch off Rough outer diameter of 3.750 diameter	8670-3

<u>Sequence Number</u>	<u>Operation</u>	<u>Tool Number</u>
300	Touch off Rough bottom of 10 degree pocket Part load position Load new tool Number 4 Load tape Number 5 finish Block delete switch on	8670-3 8670-4
305	Touch off Finish sides of 10 degree pocket	8670-4
307	Touch off Finish bottom of pocket Part load position Load new tool Number 3 Load tape Number 1 finish Block delete switch on	8670-4 8670-3
310	Touch off Finish narrow pocket	8670-3
320	Touch off Finish bottom pocket	8670-3
330	Touch off Finish upper left hand pocket Part load position Load tape Number 1A finish Block delete switch on	8670-3
340	Touch off Finish top pocket Part load position Load tape Number 2 finish Block delete switch on	8670-3
410	Touch off Finish 3.750 bore Part load position Load tape Number 3 finish Block delete switch on	8670-3
510	Touch off Finish periphery first half Part load position Load tape Number 3A finish Block delete switch on	8670-3

<u>Sequence Number</u>	<u>Operation</u>	<u>Tool Number</u>
530	Touch off Finish periphery second half Part load position Load tape Number 4 finish Load cutter Number 1 (1/4 end mill) Block delete switch on	8670-3
630	Touch off Clean out 1/8 inch radius (three places) Part load position Load tape Number 4A finish Block delete switch on	8670-1
650	Touch off Clean out 1/8 inch radius (three places) Part load position Load new part Load tape Number 1 rough Load cutter Number 2	8670-1

Appendix D

LOCKHEED PROCESSING PRODUCTION NOTES

FIRST PART MACHINED

Climb cutting was used on all roughing operations and conventional cutting was used for finishing.

Walls were 0.003 to 0.007 inch (0.076 to 0.179 mm) undersized.

The program will be corrected.

Walls of the 10 degree pocket were milled with a ball mill and had a very rough finish probably due to excessive tool contact around the ball nose.

The outside surface of the 0.020-0.030-0.040 (0.51-0.76-1.02) wall was noted to be very rough.

On succeeding parts it was decided to reduce the flute length of the finish end mill to 0.150 inch. This would reduce surface contact of the sides of the end mill with wall and consequently improve the surface finish.

An undercut was noted at the 0.100-inch thick wall by 3.75 inches long by 1.25 inches deep (2.54 by 95.2 by 31.75 mm).

The program will be corrected.

Undercuts and chattering were noted in some corners and short cuts.

It was decided to change to climb cutting on all finishing cuts to see if it would improve this condition.

The 0.125 (3.175) corner radius was machined at 30,000 rpm (3142 rad/s).

SECOND PART MACHINED

The condition noted in first part machined (walls of the 10 degree pocket were milled with a ball mill and had a very rough finish probably due to excessive tool contact around the ball nose) is again noted here.

On succeeding parts it was decided to finish the inside of the walls of this pocket before the outside. By this method the ball-nosed end mill used on the inside would be encountering a greater wall thickness, reducing the possibility of chatter. Since the

ball-nosed end mill makes more surface contact than a regular end mill and consequently exerts more of a load, the cutting operation was sequenced to favor the inside finishing with the additional rigidity.

The feed rate was changed to 120 ipm (3048 mm/min.) from 80 ipm (2032 mm/min).

The 10 degree pocket was reprogrammed to leave 0.010 to 0.020 inches (0.254 to 0.508 mm) material for finishing instead of 0.625 inches (15.8 mm). This reprogramming would result in less surface contact with milling cutters which would result in a better finish.

On succeeding parts it was decided to climb cut all finish cuts.

THIRD PART MACHINED

Cutter compensation of 0.010 (0.254 mm) was used to finish the side walls of the 10 degree pocket until the program could be changed.

Numerically controlled tape was modified to leave clean-up cut on sidewalls of 10 degree pocket.

Severe chatter was noted on the outside periphery. The 0.020 (0.508 mm) wall cracked.

FOURTH PART MACHINED

The feed rate of the ball-nosed end mill was reduced 50 percent from 120 to 60 ipm (3048 to 1524 mm/min.), and was continued on all succeeding parts. This feed rate change reduced tool chatter caused by excessive tool contact.

Climb cutting was employed on the outside periphery with a short flute (0.200 inch or 5.08 mm long) end mill.

Tool impact was noted in the upper left hand corner of the part. A 0.150 inch (3.81 mm) X-axis offset had been omitted and the NC tape was corrected.

The large cavity in the lower section of the part was potted with silastic J-compound in an attempt to determine what effect, if any, it would have on tool chatter along the 0.020-0.030-0.040 (0.5-0.76-1.02) wall. The decision to use potting material in the cavity was discussed with Bendix representatives who were witnessing the test. Mr. J. Paul of Bendix approved the decision.

Tool chatter was noted along the 0.020-0.030-0.040 wall although the cavity had been potted. On all succeeding parts the use of potting was discontinued, and conventional cutting was substituted for climb using the modified end mill (0.200 inch long flutes).

The coolant used was Cutz oil, WS 500, purchased from Rustlick Company, Los Angeles, California. The ratio of water to coolant was 10 to 1.

FIFTH PART MACHINED

This part was acceptable; no changes were made.

SIXTH PART MACHINED

It was decided to try a range of cutting depths in the long pocket, 0.150 inch (3.81 mm), 0.200 inch (5.08), and 0.250 inch (6.35 mm) deep at 120 ipm (3048 mm/min.). The 0.150 inch and 0.200 inch (3.81 and 5.08 mm) cutting depth appeared satisfactory, but tool chatter was experienced at the 0.250 inch (6.35 mm) cutting depth.

On succeeding parts, the cutting depth was 0.200 inch (5.08 mm) in this area.

SEVENTH PART MACHINED

This part was acceptable; no changes were made.

EIGHTH PART MACHINED

The outside peripheral cut was inadvertently started with a long fluted end mill with a 0.200 inch (5.08 mm) depth of cut. The operation was stopped and a short flute end mill was substituted. This procedure resulted in a slight step at the top of the outside walls.

SUMMARY OF PROCESS DEVELOPMENT

Minimization of tool contact cutting surface is essential to a satisfactory surface finish in thin wall high-speed machining. A flute length no greater than a 1.5 inch (38.1 mm) times depth of cut is desirable.

For this test part and probably for parts with a similar configuration, feed rates beyond 120 ipm and depth of cuts greater than 0.200 inch are not feasible with the equipment used.

Climb cutting is recommended for roughing cuts, but conventional cutting appears to provide a better surface on finish cutting. While conventional cutting in a "nonhigh-speed" mode would tend to undercut, high-speed machining would not, since the light loads encountered avoid the tendency of the cutting edge to "dig in."

Appendix E

BENDIX PROCESSING PRODUCTION NOTES

FIRST PART MACHINED

1. The first part was run to try out the numerical control tapes.
2. Climb cuts were used on all roughing and finishing operations.
3. All programmed feed rates were reduced during NC tape try-out.
4. The flutes on the 0.406 inch (10.319 mm) diameter drill packed with chips during the drilling operation. It was decided to blow off excess chips using an air hose during each programmed retraction from the hole.
5. The 0.600 inch (15.24 mm) diameter ball end mill duplicated some of the cuts previously made by the 0.750 inch (19.05 mm) diameter end mill.
6. The 0.250 inch (6.35 mm) diameter end mill broke during the finish cutting operation. The part was completed and a new tape (55047-B) was ordered.
7. The second finish tape (55060-A) was tried out on part 002 by mistake.
8. The spindle key lock position was not properly programmed. The part was completed and a new tape was ordered.
9. The thin wall sections of the part crowded away from the cutter during machining. This resulted in thick walls in these areas.
10. The upper and lower pockets were filled with RIGIDAX to support the thin wall sections during machining.
 - a. The volume of RIGIDAX used was too large. This resulted in excessive shrinkage of the supporting material.
 - b. The thin wall sections were still too thick in some areas and the large hole was distorted in shape.
11. Filler blocks 6985166-004 and 6985166-005 were ordered to reduce the volume of RIGIDAX required to support the thin wall sections.
12. The part was again filled with RIGIDAX using the filler blocks. This resulted in more satisfactory support of the thin walls.

13. The filler blocks and RIGIDAX were removed after machining.
14. Inspection revealed the thin wall sections were not to print due to crowding on the first finish operation.
15. It was decided to continue running parts rather than to buy additional tooling to support the walls on the first milling operation. Lack of additional tooling would not affect feeds and speeds, but would reduce part quality in the thin wall areas.

SECOND PART MACHINED

1. This part was rough machined using the original copy of the NC roughing tape to evaluate programmed feeds, speeds, and depths of cut.
2. All cuts were executed at the programmed feed rates with the following exceptions:
 - a. The 0.406 inch (10.319 mm) diameter drill was run at 40 percent of the programmed feed rate.
 - b. The 0.750 inch (19.05 mm) end mill and the 0.600 inch (15.24 mm) ball end mill feed rates were reduced 40 percent for the first full diameter cut.
 - c. The 0.250 inch (6.35 mm) diameter end mill was run at 50 percent of the programmed feed rate.
3. The revised tape (55047-B) for the first finish operation was run at 100 percent on all feed rates.
4. This part was remachined so that the machining operations could be filmed.
5. This part was potted, using RIGIDAX and the filler blocks and finish machined.

THIRD PART MACHINED

1. This part was rough machined with revised tape (55054-B) which modified some feed rates and eliminated some machining cuts.
2. An accelerometer was attached to the spindle housing to monitor spindle vibration during the machining operations.
3. The 0.600 inch (15.24 mm) diameter ball end mill slipped in the tool holder during machining. The tool was reset, and the three-dimensional pocket was recut.

4. The two finish-machining operations were run at 100 percent feed rate on all cuts without processing assistance.

FOURTH PART MACHINED

1. This part was setup and rough machined.
2. The two finish operations were run at 100 percent feed rate.

FIFTH PART MACHINED

1. This part was rough machined for observation by the Tape Optimization Committee.
2. The 0.600 inch (15.24 mm) diameter ball end mill broke during machining.
3. The automatic tool change malfunctioned during machining and caused some delay.

SIXTH PART MACHINED

1. This part was machined using a new tape (55064-A) supplied by the Tape Optimization Committee.
2. The 0.750 inch (19.05 mm) diameter end mill became packed with chips during machining and produced some molten material. The tool was shortened and the tape was run twice to reach full depth.
3. Machine malfunctions caused some delay.
4. The spindle rpm was reduced 50 percent of the programmed value on most cuts for experimenting with various feed rate changes.
5. Finish operations have not been performed on this part.

SEVENTH PART MACHINED

1. This part was rough machined with revised tape 55064-B supplied by the Tape Optimization Committee. Process representatives were not present during the operation.

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Appendix F

HIGH SPEED MILLING TEST, PHASE II

HIGH SPEED MILLING TEST - PHASE II

END MILL TYPE - 8670-2-4 & 5										WORK PIECE	
DIAMETER - 0.750 IN. NO. OF FLUTES - 2 FLUTE LENGTH - 0.75 IN. OVERALL LENGTH - 4.0 IN.					MATERIAL - CARBIDE					MATERIAL - 6061-T651 AL. SIZE - 16" x 11" x 3"	
SEQ. NO.	CUT WIDTH IN.	CUT DEPTH IN.	CUTTER SPEED RPM	TABLE SPEED IN/MIN.	CHIP LOAD IN.	SPECIMEN LOAD LBS.			CUTTING OPER.	SPINDLE HP*	COMMENTS
						X	Y	Z			
010A	.75	.050	24,000	40	.0008	4.4	24.0	0	Rough Bore	3.7	
						4.5	23.0	0	Rect	3.7	
						4.8	23.0	0		3.7	
					Av	4.6	23.3	0		3.7	
010B	.35-.65	.050	24,000	40	.0008	2.6	No data	0	Rough Bore	4.8	
						2.7	-	0	Octagonal	4.3	
						2.7	-	0		4.8	
					Av	2.7	-	0		4.6	
010B	.35-.65	.050	24,000	40	.0008	2.5	7.6	0	Rough Bore	3.0	
						2.5	8.0	0	Octagonal	3.0	
						2.5	9.0	0		3.0	
					Av	2.5	8.2	0		3.0	
020	.75	.100	24,000	120	.0025	5.0	2.1	16.9	Rough Narrow Pocket	5.5	
						4.8	3.0	17.0		5.3	
						4.9	3.0	17.0		5.6	
					Av	4.9	2.7	17.0		5.5	
030	.650	.200	24,000	120	.0025	7.3	6.6	23.4	Rough Bottom Pocket	6.9	
	(.750					7.5	6.4	22.5		6.8	
	1st Pass)					8.2	6.6	25.0		6.9	
					Av	7.7	6.5	23.6		6.9	
	.650	.250	24,000	120	.0025	-	8.8	-		8.1	
040	.300	.100	24,000	120	.0025	0	10.0	0	Rough Top Left Pocket	4.1	
	(1st Pass					3.0	4.5	10.0		3.9	
	.750)					2.5	4.0	10.0		4.0	
						2.5	4.0	10.0	(Climb)	4.0	
					Av	2.7	4.2	10.0		4.0	
050	.562	.100	24,000	120	.0025	9.0	-2.2	-8.0	Rough Right Side of Part	4.1	
						9.0	-2.5	-8.0		4.1	
						9.3	-2.2	-8.2	(Climb & Conv)	4.2	
						9.1	-2.3	-8.1		4.1	

HIGH SPEED MILLING TEST — PHASE II

END MILL TYPE — 8670-3-6										WORK PIECE	
DIAMETER — 0.75 IN. NO. OF FLUTES — 2 FLUTE LENGTH — 0.75 IN. OVERALL LENGTH — 5.0 IN.					MATERIAL — CARBIDE					MATERIAL — 6061-T651A SIZE — 16" x 11" x 3"	
SEQ. NO.	CUT WIDTH IN.	CUT DEPTH IN.	CUTTER SPEED RPM	TABLE SPEED IN/MIN.	CHIP LOAD IN.	SPECIMEN LOAD LBS.			CUTTING OPER.	SPINDLE HP *	COMMENTS
						X	Y	Z			
210A	.75	.050	24,000	40	.0008	2.6	7.2	2.0	Rough	3.1	
						2.7	7.2	1.7	Bore Through	3.1	
						2.7	7.2	1.7	Rect	3.1	
					Av	2.7	7.2	1.8	(Climb)	3.1	
210B	.35-.65	.050	24,000	40	.0008	0	1.4	1.9	Rough	2.6	
						0	1.3	2.1	Bore Through	2.6	
						0	1.4	2.1	Octagonal	2.6	
					Av	0	1.4	2.0		2.6	
220	.75	.100	24,000	120	.0025	-0.7	-2.0	-15.0	Rough	4.2	
						-0.8	-1.7	-15.5	Narrow	4.2	
						-1.0	-1.5	-13.8	Pocket	4.1	
					Av	-0.8	-1.7	-14.8	(Climb)	4.2	
230	.500	.100	24,000	120	.0025	3.5	-2.8	12.8	Rough	4.7	
	(.750					3.9	-3.0	12.9	Bottom	4.7	
	1st					3.9	-3.0	12.9	Pocket	4.7	
	Pass)				Av	3.8	-2.9	12.9	(Conv)	4.7	
250	.562	.100	24,000	120	.0025	-14.5	-2.3	3.4	Rough	4.2	
						-15.0	-2.5	3.2	Right Side	4.3	
						-15.0	-2.5	3.0	(Climb &	4.3	
					Av	-14.8	-2.4	3.2	Conv)	4.3	
260	.300	.100	24,000	120	.0025	-9.5	-1.5	-6.5	Rough	3.8	
						-9.6	-1.7	-6.6	Top	3.8	
						-9.7	-1.7	-6.5	(Climb &	3.8	
					Av	-9.6	-1.6	-6.5	Conv)	3.8	
270	.700	.100	24,000	120	.0025	1.8	-2.0	12.0	Profile	4.3	
						1.5	-2.5	13.3	Top	4.4	
						1.6	-2.5	13.5	(Climb &	4.4	
					Av	1.6	-2.3	12.9	Conv)	4.4	

HIGH SPEED MILLING TEST — PHASE II

END MILL TYPE — 8670-3-6										WORK PIECE	
DIAMETER — 0.75 IN. NO. OF FLUTES — 2 FLUTE LENGTH — 0.75 IN. OVERALL LENGTH — 5.0 IN.					MATERIAL — CARBIDE					MATERIAL — 6061-T651A SIZE — 16" x 11" x 3"	
SEQ. NO.	CUT WIDTH IN.	CUT DEPTH IN.	CUTTER SPEED RPM	TABLE SPEED IN/MIN.	CHIP LOAD IN.	SPECIMEN LOAD LBS.			CUTTING OPER.	SPINDLE HP*	COMMENTS
						X	Y	Z			
280	.300	.100	24,000	120	.0025	0	4.0	2.8	Rough	2.9	
						0	4.0	3.1	Top	2.8	
						0	4.5	3.7	Pocket	2.9	
					Av	0	4.2	3.2	(Climb & Conv)	2.9	
290	.750	.100	24,000	40	.0008	8.7	-0.2	0	Rough	3.9	
						8.8	-0.5	0	O.D. of	4.0	
						10.2	-0.7	0	Round	4.0	
					Av	9.2	-0.5	0	(Climb & Conv)	4.0	
300	.400	.100	24,000	120	.0025	16.8	36.5	7.5	Rough	4.4	
						17.0	37.0	7.5	Bottom	4.5	
						17.0	36.5	7.4	of 10° Pocket	4.4	
					Av	16.9	36.7	7.5	(Climb & Conv)	4.4	
310	.062	.100	24,000	80	.0017	1.6	0	-1.3	Finish	2.1	
						1.6	0	-1.2	Narrow	2.1	
						1.8	0	-1.2	Pocket	2.1	
					Av	1.7	0	-1.2		2.1	
320	.500	.100	24,000	80	.0017	0	-1.5	-7.5	Finish	3.3	
						0	-1.7	-8.4	Bottom	3.2	
						0	-1.7	-8.2	Pocket	3.2	
					Av	0	-1.6	-8.0	(Climb)	3.2	
330	.500	.100	24,000	80	.0017	-1.3	-1.3	7.5	Finish	2.2	
						-1.5	-1.3	7.5	Upper Left	2.2	
						-1.5	-1.5	7.5	Pocket	2.2	
					Av	-1.4	-1.4	7.5	(Climb)	2.2	
340	.500	.100	24,000	80	.0017	0.5	-0.8	6.0	Finish	3.0	
						0.3	-0.8	7.0	Top	3.1	
						0.3	-0.8	7.5	Pocket	3.1	
					Av	0.4	-0.8	6.8	(Climb)	3.1	
410	.500	.100	24,000	40	.0008	-1.4	0.6	4.0	Finish	3.0	
						-1.4	0.6	4.0	3.750	3.0	
						-1.5	0.6	3.2	Bore	3.0	
					Av	-1.4	0.6	3.7	(Climb)	3.0	

HIGH SPEED MILLING TEST — PHASE II

END MILL TYPE — 8670-3-3										WORK PIECE	
DIAMETER — 0.75 IN. NO. OF FLUTES — 2 FLUTE LENGTH — 0.20 IN. OVERALL LENGTH — 5.0 IN.					MATERIAL — CARBIDE					MATERIAL — 6061-T651 Al SIZE — 16" x 11" x 3"	
SEQ. NO.	CUT WIDTH IN.	CUT DEPTH IN.	CUTTER SPEED RPM	TABLE SPEED IN/MIN.	CHIP LOAD IN.	SPECIMEN LOAD LBS.			CUTTING OPER.	SPINDLE HP*	COMMENTS
						X	Y	Z			
510	.500	.100	24,000	80	.0017	-0.6	-1.7	-9.3	Climb	3.7	
						-1.0	-2.6	-14.2	Mill	4.3	
						-0.5	-3.0	-15.2	Outside	4.2	
					Av	-0.7	-2.4	-12.9	Bottom Web	4.1	
510	.500	.100	24,000	80	.0017	-0.5	-2.7	-13.5	"	4.2	
						-0.0	-2.8	-44.0	Chatter	4.3	
						-0.3	-2.7	-45.0	Chatter	4.2	
					Av	-0.3	-2.7			4.2	
510	.500	.100	24,000	80	.0017	-0.2	-0.24	-10.2	"	4.2	
						-0.2	-0.24	-10.2	Rubber	4.2	
						-0.2	-0.28	-10.2	Plug to	4.2	
					Av	-0.2	-0.25	-10.2	Support Wall	4.2	
510	.500	.100	24,000	80	.0017	6.7	-1.4	8.8	Conv	3.7	
						6.7	-1.4	9.0	Mill	3.8	
						6.8	-1.4	8.5	Outside	3.7	
					Av	6.7	-1.4	8.8	Bottom Web (Climb)	3.7	
530	.500	.100	24,000	80	.0017	6.8	-1.5	8.5	Conv	3.7	
						6.8	-1.5	8.3	Mill	3.7	
						6.7	-1.5	8.3	Outside	3.7	
					Av	6.8	-1.5	8.4	Bottom Web (Conv)	3.7	
610	NO DATA RECORDED										

HIGH SPEED MILLING TEST — PHASE II

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HIGH SPEED MILLING TEST - PHASE II

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Appendix G

SUMMARY OF BENDIX DATA

Table G-1.. Summary of Statistical Data for Bendix Produced Part

	Part Number						
	1	2	3	4	5	6	Average
Pocket A							
Bottom							
Mean	-0.0599	-0.0378		-0.0544	-0.0671	-0.0813	-0.0603
Standard Deviation	0.0069	0.0089		0.0378	0.0508	0.0115	0.0323
Number of Points	49	49		49	49	49	245
Walls							
Mean	-0.0021	0.0169		0.0041	0.0381	0.0632	0.0671
Standard Deviation	0.0702	0.0285		0.0980	0.0709	0.1403	0.0816
Number of Points	96	96		96	96	96	480
Radii							
Mean	0.0739	0.0041		-0.1341	-0.0514	-0.0213	-0.0258
Standard Deviation	0.1173	0.0251		0.0709	0.0726	0.0834	0.0739
Number of Points	16	16		16	16	16	80
Pocket B							
Bottom							
Mean	-0.0716	-0.0500		-0.0831	-0.0909	-0.0824	-0.0756
Standard Deviation	0.0150	0.0124		0.0074	0.0078	0.0188	0.0123
Number of Points	64	64		64	64	64	320
Walls							
Mean	-0.0390	-0.0249		0.0127	0.0460	-0.0221	-0.0080
Standard Deviation	0.0871	0.0577		0.0889	0.1166	0.1240	0.0912
Number of Points	132	132		132	90	90	576
Radii							
Mean	-0.0670	-0.0413		-0.0189	-0.0312	-0.0421	-0.0398
Standard Deviation	0.0822	0.0487		0.0900	0.0767	0.1114	0.0831
Number of Points	136	136		135	174	176	757

Table G-1 Continued. Summary of Statistical Data for Bendix Produced Part

	Part Number						
	1	2	3	4	5	6	Average
Pocket C							
Bottom							
Mean	0.0701	-0.0340		0.2141	0.0828	0.0637	0.0793
Standard Deviation	0.0094	0.0157		0.0058	0.0038	0.0047	0.0079
Number of Points	45	45		45	45	45	225
Walls							
Mean	-0.0019	-0.0439		-0.0316	-0.0208	0.0086	-0.0179
Standard Deviation	0.0839	0.0305		0.0717	0.0894	0.0882	0.0727
Number of Points	88	88		88	86	88	438
Radii							
Mean	-0.0467	-0.0389		-0.0597	-0.0523	-0.0292	-0.0454
Standard Deviation	0.0729	0.0355		0.066	0.0738	0.0502	0.0597
Number of Points	50	50		50	50	50	250
Pocket D							
Bottom							
Mean	0.0307	-0.0424		0.1910	0.0629	0.0808	0.0646
Standard Deviation	0.0081	0.0081		0.0056	0.0024	0.0042	0.0057
Number of Points	16	16		16	16	16	80
Walls							
Mean	0.1316	-0.0107		0.0358	0.0267	0.0152	0.0396
Standard Deviation	0.1604	0.0415		0.2297	0.1423	0.1248	0.1397
Number of Points	200	196		200	196	201	993
Radii							
Mean	0.0299	-0.0561		0.0058	-0.0079	0.0139	-0.0029
Standard Deviation	0.0704	0.0320		0.0465	0.0706	0.0612	0.0561
Number of Points	64	64		64	64	64	320

Table G-1 Continued. Summary of Statistical Data for Bendix Produced Part

	Part Number						
	1	2	3	4	5	6	Average
Pocket E							
Bottom							
Mean	-0.0846	-0.0693		-0.0480	-0.0859	-0.0790	-0.0734
Standard Deviation	0.0119	0.0102		0.0150	0.0063	0.0054	0.0098
Number of Points	55	55		55	55	55	275
Walls							
Mean	0.0285	0.0431		0.0525	0.0466	0.0960	0.0533
Standard Deviation	0.0805	0.0828		0.1385	0.1139	0.1373	0.1106
Number of Points	152	152		153	152	152	761
Radii							
Mean	-0.0620	-0.0452		0.0114	-0.0100	0.0041	-0.0203
Standard Deviation	0.1078	0.0749		0.0838	0.0831	0.1338	0.0967
Number of Points	128	128		127	122	128	633
Pocket F							
Bottom							
Mean	0.2926	0.2134		0.3904	0.2538	0.1507	0.2602
Standard Deviation	0.0117	0.0363		0.0102	0.0716	0.0199	0.0299
Number of Points	12	12		12	12	12	60
Walls							
Mean							
Standard Deviation							
Number of Points							
Radii							
Mean	0.0521	-0.0051		0.0396	0.0633	0.0464	0.0393
Standard Deviation	0.0523	0.0556		0.0424	0.0518	0.0443	0.0493
Number of Points	80	80		80	79	80	399

Table G-2. Summary of Statistical Data for Lockheed Produced Part

	Part Number						
	1	2	4	5	7	8	Average
Pocket A							
Bottom							
Mean	-0.2327	-0.0676	-0.2126	-0.2352	0.0724	-0.0620	-0.1229
Standard Deviation	0.0160	0.0173	0.0138	0.0729	0.0137	0.0142	0.0253
Number of Points	49	49	49	49	49	48	293
Walls							
Mean	-0.0806	-0.0933	0.0340	-0.1596	-0.0732	-0.0959	-0.0781
Standard Deviation	0.1187	0.1156	0.1392	0.0587	0.1097	0.1294	0.1118
Number of Points	96	96	93	96	96	96	573
Radii							
Mean	-0.1288	-0.1250			-0.1158	-0.1267	-0.1241
Standard Deviation	0.0940	0.0886			0.1041	0.0653	0.0880
Number of Points	16	16			16	16	64
Pocket B							
Bottom							
Mean	-0.1651	-0.0391	-0.1903	-0.2169	0.1224	-0.0251	-0.0857
Standard Deviation	0.0211	0.0157	0.0145	0.016	0.0180	0.0175	0.0171
Number of Points	64	64	64	64	64	64	384
Walls							
Mean	-0.0865	-0.1020	-0.0591	-0.0632	-0.0882	-0.0789	-0.0810
Standard Deviation	0.0854	0.0680	0.1116	0.1063	0.0826	0.0998	0.0910
Number of Points	129	130	82	128	130	132	731
Radii							
Mean	0.0021	0.0102	-0.0291	0.0076	-0.0105	-0.0414	-0.011
Standard Deviation	0.1471	0.1279	0.2319	0.0837	0.1166	0.1040	0.1378
Number of Points	136	136	140	104	134	136	786

Table G-2 Continued. Summary of Statistical Data for Lockheed Produced Part

	Part Number						
	1	2	4	5	7	8	Average
Pocket C							
Bottom							
Mean	-0.1105	0.0056	-0.1796	0.0950	0.0798	-0.0218	-0.0263
Standard Deviation	0.0089	0.0180	0.0115	0.0135	0.0132	0.0091	0.0124
Number of Points	45	45	45	45	45	45	270
Walls							
Mean	-0.0564	-0.0574	-0.0446	-0.0383	-0.0580	-0.0950	-0.0583
Standard Deviation	0.0872	0.1539	0.1503	0.0663	0.0963	0.1407	0.1158
Number of Points	88	81	88	88	88	89	521
Radii							
Mean	0.0442	0.0777	0.0578	0.2332	0.0511	-0.1250	0.0565
Standard Deviation	0.0869	0.0973	0.1699	0.1453	0.1105	0.2093	0.1365
Number of Points	50	50	50	49	49	50	298
Pocket D							
Bottom							
Mean	-0.2365	0.0036	-0.1496	-0.1885	0.1473	0.0069	-0.0043
Standard Deviation	0.0114	0.0076	0.0054	0.0041	0.0213	0.0066	0.0094
Number of Points	16	16	16	16	16	16	96
Walls							
Mean	0.0002	0.0055	-0.0403	-0.0149	0.0128	0.0345	-0.0004
Standard Deviation	0.1076	0.0860	0.1153	0.0398	0.0860	0.0916	0.0877
Number of Points	200	200	200	200	200	128	1128
Radii							
Mean	0.0424	0.0434	0.0712	0.0533	0.0467	-0.0084	0.0414
Standard Deviation	0.1031	0.1024	0.1842	0.0759	0.1140	0.1265	0.1177
Number of Points	64	64	64	64	63	64	383

Table G-2 Continued. Summary of Statistical Data for Lockheed Produced Part

	Part Number						
	1	2	4	5	7	8	Average
Pocket E							
Bottom							
Mean	-0.2476	-0.0163	-0.1670	-0.2002	0.1626	0.0074	-0.0769
Standard Deviation	0.0102	0.0076	0.0059	0.0066	0.0185	0.0069	0.0093
Number of Points	55	57	55	55	56	55	333
Walls							
Mean	-0.0649	-0.0575	0.0430	-0.0049	-0.0448	-0.1296	-0.0431
Standard Deviation	0.0440	0.0536	0.1267	0.1489	0.0491	0.0516	0.079
Number of Points	152	152	152	152	152	151	911
Radii							
Mean	-0.0472	-0.0526	0.0018	-0.0109	-0.0221	-0.0584	-0.0316
Standard Deviation	0.1323	0.1303	0.1611	0.0792	0.1735	0.1735	0.1490
Number of Points	128	128	127	127	128	128	766
Pocket F							
Bottom							
Mean	-0.1196	-0.2647	0.0555	-0.2286	-0.0160	-0.0363	-0.1016
Standard Deviation	0.0376	0.4663	0.0573	0.0378	0.0589	0.0437	0.1169
Number of Points	12	12	12	12	9	12	69
Walls							
Mean							
Standard Deviation							
Number of Points							
Radii							
Mean	-0.1603	-0.1905	-0.1366	-0.0884	-0.1740	-0.1816	-0.1552
Standard Deviation	0.0968	0.0922	0.0674	0.0467	0.1270	0.1059	0.0893
Number of Points	80	80	79	77	76	78	470

Table G-3. Dimensional Inspection Data Summary

Measured Area	Bendix Parts			Lockheed Parts		
	Mean	Standard Deviation	Parts	Mean	Standard Deviation	Parts
Pocket A						
Bottom	-0.0603	0.0323	245	-0.1229	0.0253	292
Walls	0.0671	0.0816	480	-0.0781	0.1118	573
Radii	-0.0258	0.0739	80	-0.1241	0.088	64
Pocket B						
Bottom	-0.0756	0.0123	320	-0.0857	0.0171	384
Walls	-0.008	0.0912	576	-0.081	0.0910	731
Radii	-0.0398	0.0831	757	-0.011	0.1378	786
Pocket C						
Bottom	0.0793	0.0079	225	-0.0263	0.0124	270
Walls	-0.0179	0.0727	438	-0.0583	0.1158	521
Radii	-0.0454	0.0597	250	0.0565	0.1365	298
Pocket D						
Bottom	0.0646	0.0057	80	-0.0043	0.0094	96
Walls	0.0396	0.1397	993	-0.0004	0.0877	1128
Radii	-0.0029	0.0561	320	0.0414	0.1177	383
Pocket E						
Bottom	-0.0734	0.0098	275	-0.0769	0.0093	333
Walls	0.0533	0.1106	761	-0.0431	0.079	911
Radii	-0.0203	0.0967	633	-0.0316	0.149	766

Table G-3 Continued. Dimensional Inspection Data Summary

Measured Area	Bendix Parts			Lockheed Parts		
	Mean	Standard Deviation	Parts	Mean	Standard Deviation	Parts
Pocket F						
Bottom	0.2602	0.0299	60	-0.1016	0.1169	69
Radii	0.0393	0.0493	399	-0.1552	0.0893	470

Table G-4. Maximum and Minimum Deviation From Nominal Dimensions
for Bendix Parts

	Bendix Part Number						
	001	002	004	005	006	Tolerance	Range
Pocket A							
Bottom	-0.0019	-0.0010	+0.0022	+0.0032	-0.0026	±0.005	+0.0032
	-0.0031	-0.0022	-0.0034	-0.0040	-0.0053		-0.0053
Walls	+0.0056	+0.0049	+0.0067	+0.0067	+0.0051	±0.003	+0.0067
	-0.0057	-0.0017	-0.0050	-0.0028	-0.0026		-0.0057
Radii	+0.0025	+0.0015	+0.0005	+0.0023	+0.0022	±0.003	+0.0025
	-0.0129	-0.0017	-0.0077	-0.0070	-0.0070		-0.0129
Pocket B							
Bottom	-0.0019	-0.0010	-0.0024	-0.0029	-0.0021	±0.005	-0.0010
	-0.0037	-0.0031	-0.0039	-0.0040	-0.0042		-0.0042
Walls	+0.0088	+0.0227	+0.0110	+0.0078	+0.0058	±0.003	+0.0227
	-0.0089	-0.0061	-0.110	-0.0045	-0.0076		-0.0110
Radii	+0.0044	+0.0044	+0.0062	+0.0064	+0.0060	±0.003	-0.0103
	-0.0103	-0.0099	-0.0087	-0.0068	-0.0097		-0.0103
Pocket C							
Bottom	+0.0035	-0.0009	+0.0091	+0.0035	+0.0029	±0.005	+0.0091
	+0.0021	-0.0028	+0.0078	+0.0029	+0.0021		-0.0028
Walls	+0.0075	+0.0011	+0.0058	+0.0051	+0.0088	±0.003	+0.0088
	-0.0046	-0.0049	-0.0052	-0.0059	-0.0046		-0.0059
Radii	+0.0024	-0.0001	+0.0011	+0.0038	+0.0027	±0.003	+0.0038
	-0.0055	-0.0027	-0.0078	-0.0064	-0.0043		-0.0078

Table G-4 Continued. Maximum and Minimum Deviation From Nominal Dimensions for Bendix Parts

	Bendix Part Number						
	001	002	004	005	006	Tolerance	Range
Pocket D							
Bottom	+0.0019	-0.0013	+0.0079	+0.0027	+0.0035	<u>+0.005</u>	+0.0079
	+0.0009	-0.0022	+0.0072	+0.0024	+0.0030		-0.0022
Walls	+0.0211	+0.0058	+0.0170	+0.0160	+0.0162	<u>+0.003</u>	+0.0211
	-0.0121	-0.0055	-0.0033	-0.0070	-0.0063		-0.0121
Radii	+0.0078	+0.0003	+0.0033	+0.0048	+0.0051	<u>+0.003</u>	+0.0078
	-0.0026	-0.0044	-0.0033	-0.0042	-0.0050		-0.0050
Pocket E							
Bottom	-0.0024	-0.0015	-0.0015	-0.0029	-0.0026	<u>+0.005</u>	-0.0015
	-0.0041	-0.0034	-0.0025	-0.0038	-0.0034		-0.0041
Walls	+0.0123	+0.0122	+0.0164	+0.0137	+0.0145	<u>+0.003</u>	+0.0164
	-0.0081	-0.0076	-0.0154	-0.0039	-0.0078		-0.0081
Radii	+0.0063	+0.0034	+0.0058	+0.0061	+0.0078	<u>+0.003</u>	+0.0078
	-0.0100	-0.0090	-0.0059	-0.0063	-0.0119		-0.0119
Pocket F							
Bottom	+0.0121	+0.0105	+0.0160	+0.0114	+0.0068	<u>+0.005</u>	+0.0160
	+0.0106	+0.0055	+0.0146	+0.0096	+0.0044		+0.0044
Walls						<u>+0.003</u>	x
							x
Radii	+0.0052	+0.0082	+0.0045	+0.0065	+0.0057	<u>+0.003</u>	+0.0082
	-0.0024	-0.0037	-0.0030	-0.0024	-0.0022		-0.0037

Table G-5. Maximum and Minimum Deviation From Nominal Dimensions for Lockheed Parts

Lockheed Part Number								
	001	002	004	005	007	008	Tolerance	Range
Pocket A								
Bottom	-0.0078	-0.0014	-0.0073	-0.0086	+0.0042	-0.0014	+0.005	+0.0042
	-0.0104	-0.0039	-0.0093	-0.0107	+0.0013	-0.0035		-0.0107
Walls	+0.0052	+0.0064	+0.0118	+0.0107	+0.0070	+0.0050	+0.003	+0.0118
	-0.0108	-0.0124	-0.0067	-0.0056	-0.0105	-0.0128		-0.0128
Radii	-0.0002	-0.0006	ND	ND	+0.0014	-0.0010	+0.003	+0.0014
	-0.0100	-0.0097	ND	ND	-0.0101	-0.0083		-0.0101
Bottom	-0.0048	-0.0006	-0.0065	-0.0073	+0.0062	-0.0001	+0.005	+0.0062
	-0.0078	-0.0032	-0.0089	-0.0100	+0.0035	-0.0025		-0.0100
Walls	+0.0045	+0.0041	+0.0065	+0.0130	+0.0043	+0.0045	+0.003	+0.0130
	-0.0089	-0.0097	-0.0169	-0.0121	-0.0112	-0.0112		-0.0169
Radii	-0.0169	-0.0135	-0.0206	-0.0063	-0.0120	-0.0108		-0.0206
Pocket C								
Bottom	-0.0038	+0.0006	-0.0064	+0.0046	+0.0040	+0.0017	+0.005	+0.0046
	-0.0054	-0.0006	-0.0080	+0.0028	+0.0021	+0.0001		-0.0080
Walls	+0.0053	+0.0056	+0.0083	+0.0026	+0.0041	+0.0080	+0.003	+0.0083
	-0.0093	-0.0120	-0.0120	-0.0085	-0.0088	-0.0158		-0.0158
Radii	+0.0097	+0.0112	+0.0104	+0.0183	+0.0107	+0.0066	+0.003	+0.0183
	-0.0050	-0.0044	-0.0106	-0.0028	-0.0066	-0.0262		-0.0262

Table G-5 Continued. Maximum and Minimum Deviation From Nominal Dimensions for Lockheed Parts

	Lockheed Part Number							
	001	002	004	005	007	008	Tolerance	Range
Pocket D								
Bottom	-0.0087	+0.0005	-0.0058	-0.0072	+0.0070	+0.0008	<u>+0.005</u>	+0.0070
	-0.0101	-0.0006	-0.0063	-0.0077	+0.0045	-0.0001		-0.0101
Walls	+0.0052	+0.0046	+0.0072	+0.0028	+0.0054	+0.0036	<u>+0.003</u>	+0.0072
	-0.0075	-0.0077	-0.0151	-0.0046	-0.0062	-0.0156		-0.0156
Radii	+0.0096	+0.0099	+0.0157	+0.0073	+0.0114	+0.0076	<u>+0.003</u>	+0.0157
	-0.0057	-0.0064	-0.0105	-0.0045	-0.0066	-0.0137		-0.0137
Pocket E								
Bottom	-0.0090	-0.0001	-0.0061	-0.0072	+0.0074	+0.0009	<u>+0.005</u>	+0.0009
	-0.0105	-0.0011	-0.0072	-0.0086	+0.0047	-0.0002		-0.0105
Walls	+0.0017	+0.0031	+0.0122	+0.0204	+0.0033	+0.0012	<u>+0.003</u>	+0.0204
	-0.0074	-0.0075	-0.0074	-0.0149	-0.0070	-0.0131		-0.0149
Radii	+0.0096	+0.0098	+0.0104	+0.0082	+0.0094	+0.0249	<u>+0.003</u>	+0.0249
	-0.0133	-0.0135	-0.0097	-0.0073	-0.0108	-0.0106		-0.0135
Pocket F								
Bottom	-0.0025	+0.0001	-0.0011	-0.0069	+0.0026	+0.0009	<u>+0.005</u>	+0.0026
	-0.0080	-0.0207	-0.0123	-0.0124	-0.0051	-0.0048		-0.0207
Walls							<u>+0.003</u>	x
Radii	+0.0089	+0.0005	+0.0063	-0.0016	+0.0117	+0.0017	<u>+0.003</u>	x
	-0.0119	-0.0126	-0.0025	-0.0071	-0.0122	-0.0135		+0.0117
								-0.0135

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PRELIMINARY STUDY OF HIGH SPEED MACHINING,
R. E. Jordan, Milestone, July 1980

The feasibility of a high speed machining process has been established for application to Bendix aluminum products, based upon information gained through visits to existing high speed machining facilities and by the completion of a representative Bendix part using this process. The need for an experimental high speed machining capability at Bendix for further process evaluation is established.

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