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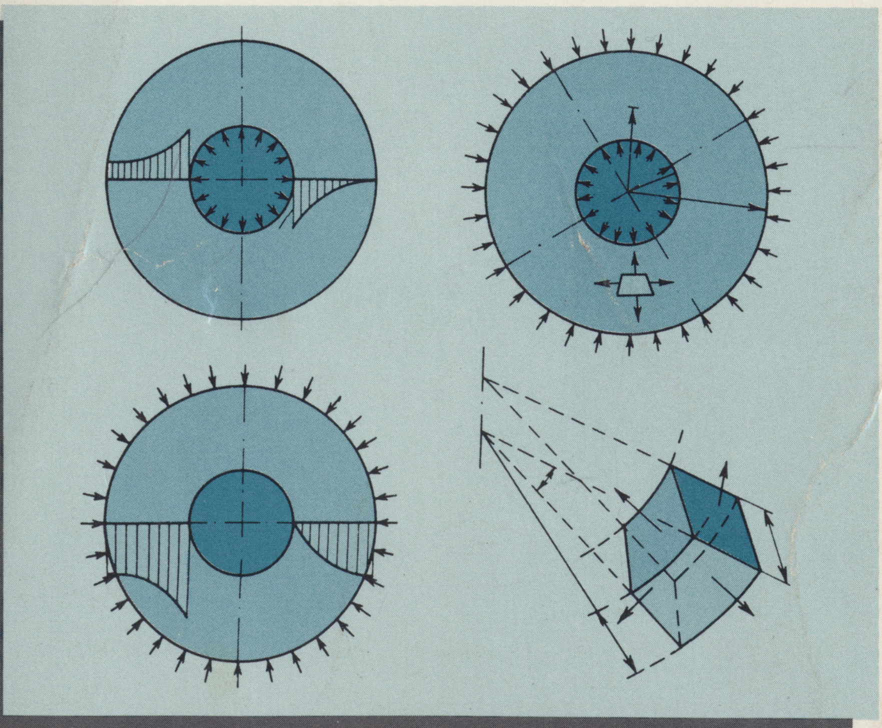

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FOREWORD

During the last few decades, the principal breakthroughs in material processing have been brought about by the development of casting, forming, and material deposition. Now the most important advances in the processing of structural, electronic, photonic, and biological materials can be expected in material removal. Material removal is the only technology that orthogonalizes the control of material properties and geometry. Thus, it enables simultaneous generation of components with special geometry, for example ultra-precision parts with exotic shapes and parts of materials with special properties. Shaping of materials is a key part of almost any significant manufacturing process. Choice of materials, cost of manufacture, functionality, quality, and environmental impact, all depend strongly on the ability to shape materials in a manufacturing environment.

Thermodynamic analysis of material-removal technology and common sense indicate that the ideal tool for material shaping is a high energy beam, with an infinitely narrow cross-section, precisely-controlled depth and direction of penetration, that leaves no effect on the generated surface. In addition, production of the beam should be relatively inexpensive and free of environmental impact. No such beam exists currently.

A high-energy beam of considerable practical and theoretical interest that comes close to meeting these requirements in several important attributes is a narrow stream or jet of high-velocity water or water-particles slurry. There is an increasing need for further research into such technologies, which are becoming more widely used for shaping hard-to-machine materials and are being viewed increasingly as *conventional* rather than *non-traditional* technologies. In response to some of these concerns, the engineering community has shown a sustained interest in fluid-based machining. Despite the comparative novelty of this technique, thousands of papers concerning the use of waterjets have been published. However, the English-speaking community has not had a comprehensive description of this rather popular technology — one that is much needed for professionals entering the field as well as for those already working in this area. This book fills the gap.

High-Pressure Jetcutting considers all aspects of waterjet and abrasive waterjet machining. Technology overview, jet formation, jet-workpiece interaction, design, and operation of the facilities are each discussed. The chapter concerning facility design is perhaps the most important, because this topic is generally presented poorly in the literature of the field. As a comprehensive, fundamental description of the process of this fast-growing technology, this work is a major accomplishment.

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November, 1991

PREFACE

Nonmetallic structural materials possessing high strength are finding increasing applications in shipbuilding. However, the machining of these materials often presents a problem. Traditional material machining methods cannot always provide high productivity, and in the case of complex surfaces, these methods are simply unacceptable and hand operations can be required. This situation motivates the improvement of existing technological processes and the development of new processes for the solution of problems that exist in industry.

The utilization of the energy of a supersonic liquid jet outflowing from a small-diameter hole under high pressure is a progressive direction in material cutting. Liquid jetcutting excludes a cutting tool, the edges of which are constantly subject to wear from the technological process. The application of superhigh-pressure hydraulic systems indicates a qualitative leap in mechanical engineering, because it results in increased productivity and machining quality as well as improvements in work conditions.

The theoretical and applied development of jetcutting systems and a theory of jetcutting of various materials are based on Soviet and foreign research studies of hydraulic techniques for low, high, and superhigh pressure. The scientific foundations of liquid jetcutting were developed in studies of Soviet scientists, L. F. Vereschagin, A. A. Semertchan, G. P. Nikonov, S. S. Shavlovski, and others, and foreign investigators, N. Franz, P. D. Lee, F. Lavoie, M. Hashish, and others.

In recent years questions related to the solution of jetcutting problems have received significant attention in Soviet and foreign literature, including books, papers, certificates of invention, and patents.

In this book the authors have attempted to outline the existing research on jetcutting. They have also reported some of their observations and results of their studies of this material-machining process. The book includes information on scientific foundations and application of jetcutting for material machining.

The book enables a reader to understand the problems that exist with this interesting and prospective application of the energy of supersonic liquid jets.

Practical application of the results of theoretical and experimental studies of the jetcutting of different materials is complicated by many factors that accompany jetcutting and affect process productivity, accuracy, and the quality of machined surfaces. A scientific choice of jetcutting regimes must be based on knowledge of the physical laws of the process relating to the structure and hydrodynamics of narrow supersonic liquid jets formed by special nozzles. Data on the physical modeling of the interaction between a cutting jet and a machined material were used for the development of theoretical foundations for the machining of materials.

The book presents a classification of jetcutting methods and different schemes of the process. Momentum distribution in a supersonic jet and jet action on a machined material are considered based on a study of the force characteristics of jetcutting. Significant attention is paid to technological parameters of jetcutting that affect feed velocity and machining quality — the outflow pressure, diameter and composition of the jet, the distance between the nozzle and the machined material, the physical and mechanical properties of the material, the material thickness, and so forth.

CONTENTS

1. JETCUTTING AND ITS APPLICATIONS

1.1 USING LIQUID JET AS A CUTTING TOOL

A narrow liquid jet flowing at high velocity from a small-diameter hole can act on a material with a force sufficient to break microscopic material particles (chips) off its main bulk. This property of liquid jets motivated researchers of different countries to develop machining methods in which the jet kinetic energy is transformed into mechanical work for cutting. In general, when jet is used as a cutting tool, the jet velocity is supersonic.

Jetcutting is relatively new, and for some applications, it is very effective, but it is insufficiently studied and seldom used for the machining of different materials. The process of jetcutting is being studied and equipment is being developed and introduced to industry in the USSR and abroad. Specific problems in formation of and energy transformation in liquid jets are related to the technology of material machining by supersonic jets of various compositions and designs and to the operation of special equipment. The principal problems include:

- study of cutting process laws;
- design and development of complicated liquid supersonic systems of various functions;
- development of hydrocutting systems and machines with various characteristics;
- development of technological material jetcutting processes.

Successful studies of the use of jetcutting in different materials have been undertaken in the USSR, United States, Great Britain, West Germany, Japan, and other countries. Liquid jets can be used for the cutting of paper, board, cloth, wood, leather, rubber, plastic and ceramic materials, nonferrous alloys, and steel. Hydraulic machines with 8–80 kW of power are used for jetcutting. These machines provide jet outflow pressures of 150–1000 MPa and higher and jet velocities of 540–1400 m/s, significantly exceeding the speed of sound in air.

Nozzles with exit-hole (nozzle) diameters from 0.05 to 0.5 mm are used for qualitative and productive machining. The nozzle diameter used depends upon the machined material thickness and its physical and mechanical properties. The rate of fluid flow through the nozzle is relatively low: 500–2500 cm^3/min and dependent on the jet outflow parameters.

The first information on the possibility of using superhigh-pressure jets as a cutting tool for the machining of various materials appeared in the USSR [12]. However, jetcutting was first patented by the staff of McCartney Manufacturing Company, a division of the Ingersoll-Rand Corp., in the United States [39]. An experimental machine utilizing this method has been successfully used by this company for the cutting of various materials since 1971. The company devises industrial applications of supersonic water jets for cutting viscous and brittle nonmetallic materials and light alloys. Other U. S. companies also use narrow supersonic liquid jets for cutting plates of different materials. The British company British Shell and the British Hydromechanics Research Association use supersonic liquid jets as a cutting tool for nonmetallic material sheets to obtain small cutting widths, rational blank location and spacing, and improved quality and productivity.

Supersonic liquid jets can also be used for applications other than the cutting of nonmetallic material sheets. For example, one U.S. company applies water jets for the cleaning of aluminum and other light alloy castings. This allows it to eliminate completely mechanical damage to the blank surface. Other U. S., British, West German, and Japanese companies use liquid jetcutting to reduce the cost of sheet machining and to address problems such as the location and spacing of facing materials; material crushing; burr removal; hole punching; casting cutting; cleaning of chemical equipment, internal surfaces of pipes, and ship bottoms; finishing of blank surfaces in barely accessible places, and so forth.

The cutting capabilities of jets and jetcutting operations depend on a number of factors including the type of machined material, the composition of the working fluid, the method of machining, and the direction of the liquid jet with respect to the machined surface. Low-strength materials are easier to cut; they also require a lower jet-outflow pressure. For example, jet-outflow pressures on the order of 200 MPa are used for cutting board, plywood, leather, leather substitutes, and rubber. Pressures on the order of 200–500 MPa are used to cut plastics. Light metals are cut at 500–700 MPa and steel at 700–1000 MPa.

The composition of the working fluid, that is, the technological medium acting on a machined material, has a great effect on the jet's compactness, its cutting properties, and its capability to cut a given material. There are polymeric materials whose properties deteriorate as a result of moisture absorption. Obviously, such materials cannot be machined using water jets. In this case, various alcohols are used as cutting agents. Industrial oils are optimum for cutting blanks from unkilned ceramics. The addition of soluble polymers to water improves the productivity of sheet cutting by up to 35% and extends the technological capabilities of a liquid jet as a cutting tool.

Notably, using abrasive-liquid jets as cutting tools extends the range of machined materials significantly and reduces the required cutting pressure. For example, metals and other hard materials can be cut by such jets at pressures on the order of 250 MPa (instead of 1000 MPa), providing the same productivity as clean-water jets at a higher outflow pressure.

Jetcutting productivity can also be improved by changing the character of the action of a supersonic jet on a machined material using vibrations in the cutting zone. These vibrations can be caused by vibratory material motions or vibrations of the nozzle head, that is, the jet itself. In both cases the jet's impact on the machined material increases, and the damping effect of water pockets formed as a result of the accumulation of worked-off fluid in microscopic cracks and cavities in the cutting zone is reduced.

The impact of a destructive agent on a material can be increased by the formation of a pulsating jet. Pulsating jets generated by any method are characterized by the pulsation frequency of the jet outflow from the nozzle. Compared with continuous jets, pulsating jets have better compactness, a greater effective length of action, and higher forces on the machines material. This results in higher productivity and lower power requirements for the machining process.

Jetcutting productivity can also be increased by machining a stressed material subject to tensile loads in the direction perpendicular to the feed direction simultaneously with jetcutting. Material subject to such loads must remain within elastic limits.

Impulse jets are useful for hole punching in sheets of material. Such jets are periodically released from the nozzle to impact the machined surface. The development of impacting hydraulic machines has been intensive during this decade both in the USSR and abroad.

The machining process and productivity are also affected by the direction of the jet relative to the material or, as it is called, the angle of attack α. The following schemes of jet action on a machined material are possible during jetcutting: at an angle of attack equal to 90°, machining by an impact jet (Fig. 1.1*a*); at an angle of attack from 0–90°, machining by an oblique jet (Fig. 1.1*b*); and at an angle of attack equal to 0°, machining by a slanting jet (Fig. 1.1*c*). An increase in the angle of attack changes the character of the interaction between the jet and the machined material, the state of the machined material and the jet, and other factors that affect the intensity of destruction of the surface layer. The relationship between jetcutting productivity and the angle of attack differs for materials with different physical and mechanical properties.

A supersonic liquid jet is a very precise and accurate tool (the width of a cut may be 0.1–0.8 mm). This allows for the machining of blanks

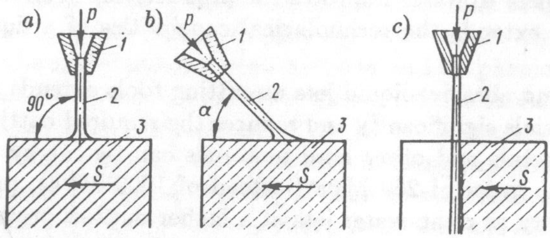

FIG. 1.1: Schemes of jet action on machined material. *1*) **nozzle;** *2*) **jet;** *3*) **machined material.**

with complex profiles and arbitrary angles of curvature, and it reduces chip volume by a factor of 15–20 compared with traditional machining. A cut can be started at any point on a machined material, and there is no necessity for an initial hole. Cutting forces are small (up to 100 N); this excludes material deformations in the zone adjacent to the cutting zone and improves machining quality. The cutting temperature (60–90°C) does not cause thermal damage in polymeric materials. In general, liquid jets do not have any negative effects on the physical and mechanical properties of a machined material.

The use of supersonic liquid jets allows automation of the machining process if it is necessary; eliminates mechanical cutting tools whose working edges are subject to wear from the technological process; saves on personnel and equipment costs for manufacturing and recutting of tools; improves machining quality; reduces chip volume, noise, and dusting; and enables cutting of details with complex profiles and different sizes.

1.2 CLASSIFICATION OF METHODS AND SCHEMES OF JETCUTTING

The multitude of operations available using liquid jetcutting and the variety of jet compositions and requirements has resulted in a large number of methods and schemes of jetcutting and the necessity for their classification.

Existing methods and schemes of liquid jetcutting depend on a number of factors, and they can be divided into the following groups:

- according to operation — cutting of sheets, slot cutting, window cutting, machining a complicated contour, hole punching, surface machining of materials and details (finishing and polishing of external surfaces, including those in barely accessible places with complicated profile details, marking);
- according to machined material — machining of soft materials (paper, board, cloth, rubber, wood, leather); machining of polymers (rigid

PVC, fluoroplastic, acrylic plastic, synthetic-resin bonded (SRB) paper laminate, cloth-base laminate, glass-reinforced plastic, and so forth); machining of foiled and metallized plastics (foiled SRB paper laminate and glass-cloth-base laminate faced at one or both surfaces, cellular plastic, and so forth); machining of hard materials (carbides, glass ceramics, magnetic materials, and so forth);

- according to working fluid composition — water machining; machining by jets of oil, glycerol, alcohol, and so forth; machining by a polymer solution in water; abrasive-liquid machining;
- according to jet action on a material — machining by a continuous jet of constant pressure; vibratory machining; machining by pulsating jets; and
- according to jet direction relative to a material — machining by an impact jet; machining by an oblique jet; machining by a slanting jet.

Each machining method should be considered taking into account the physical foundations of jetcutting, the structural scheme of the process, and the possibility of development of its mathematical model.

The structural schemes of various methods of jetcutting with a supersonic liquid jet can differ. Structural schemes of material sheet cutting by a liquid jet are shown in Fig. 1.2. The machined material (*5*) fixed on a table (*6*) moves either constantly or periodically about a supersonic jet outflowing from an exhaust nozzle (*4*). The process of cutting occurs when the jet contacts the material. The chip remains in the tank (*7*). The continuous jet at a superhigh pressure necessary for material cutting is generated by a hydrotransformer (*3* amplifier, pump) working from a low-pressure system (*2*) and controlled by the system (*1*) (Fig. 1.2*a*). The hydrotransformer is supplied with working fluid from a hydraulic supply system (*9*) through a filtration system (*8*).

For an abrasive-liquid machining system (*10*) (Fig. 1.2*b*) the preparation of the abrasive suspension is added to the scheme. The suspension is supercharged into the nozzle (*11*), where abrasive grains are absorbed by a supersonic liquid jet, accelerated, and transferred into the cutting zone.

A structural scheme using an electrohydraulic effect to punch holes in a sheet with an impulse jet is shown in Fig. 1.2*c*. The charger contour (*12*) charges a capacitor bank (*13*) to a working voltage. The principal part of electrohydraulic machines is the discharging chamber (hydrotransformer) (*3*), where a discharging device (*14*) is used for electric discharge in a liquid medium. As a result of this discharge, a jet (liquid beam) is expelled from the nozzle (*4*) with a high velocity and acts on the material (*5*) fixed on a periodically moving table (*6*). The discharging chamber is supplied from the hydraulic supply system (*9*) through the filtration system (*8*). Other, similar jetcutting schemes are also available, but they are omitted here for brevity.

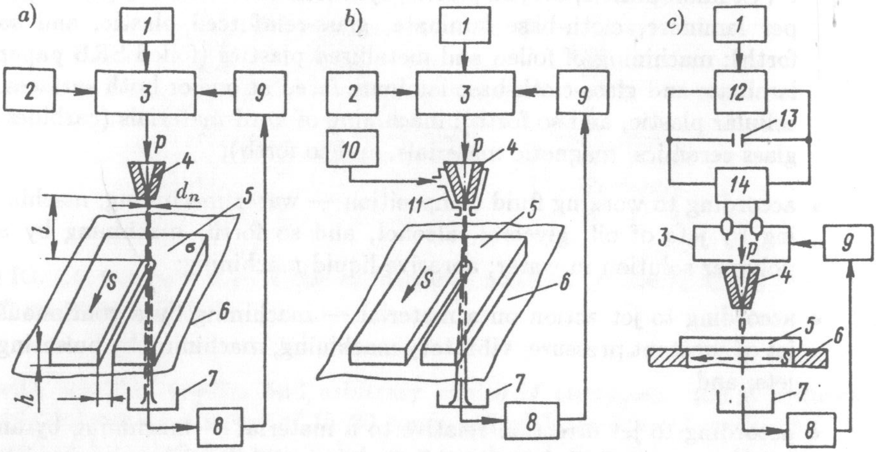

FIG. 1.2: Structural schemes of the jetcutting process.

The interaction among the input and output parameters and the jetcutting mechanisms should be accounted for during jetcutting. The input parameters include: for the machine — the model, its technical data (maximum pressure $p_{\max}$, maximum fluid flow $Q_{\max}$, required power N); for the tool — the exhaust nozzle (jet) diameter d_n, fluid composition (technical water, organic fluid, polymer solution, abrasive-liquid solution), fluid properties (density ρ, viscosity μ, concentration of components K); for the blank — its physical and mechanical properties (strength σ and thickness h). Input parameters also include the method of cutting by jet (continuous, pulsating, impulsive, with superposition of vibrations, without vibrations, with or without stressing of material, impact, oblique or slanting jet); material cutting in one pass, $n = 1$, or several passes, $n > 1$. Input parameters of cutting regimes include the jet outflow pressure p, the material feed velocity S, and the distance between the material and the nozzle (l).

Input parameters of the structural scheme are provided by a designer (machine drawing, material, machined detail dimensions, data on accuracy and roughness) and an industrial engineer (blank data, machining method, allowance, type, power and stiffness of the machine, operation scheme, working fluid composition, machining regime).

Output parameters include machining accuracy — accuracy class, cut width allowance δ_b, profile allowance δ_p; machining quality — micro-imperfection height R_z, cutting line deviation Δ_ℓ, presence of spalling, delamination, and cracks along the cutting line Δ_s; nozzle endurance — time T; cutting forces — for through-cutting P_z, for surface cutting and hole punching $P_{\max}$; cost of process — power requirements, machining cost; productivity Q_p — area of machined surface F_p and number of details n_d.

The output parameters characterize the technical requirements for a