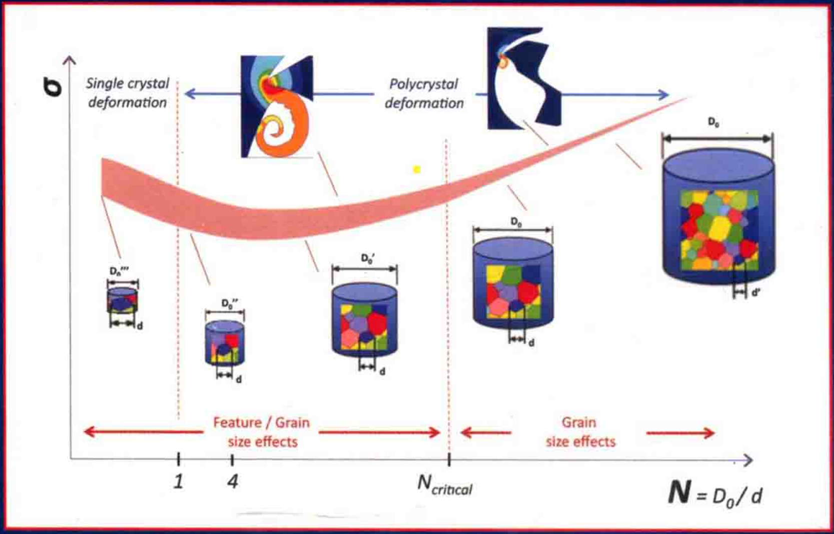
Micro-Manufacturing

Design and Manufacturing of Micro-Products



Edited by
MUAMMER KOÇ • TUĞRUL ÖZEL

WILEY

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MICRO-MANUFACTURING

FOREWORD

Since early 1990s, there has been an increasing demand for compact, integrated and miniature products for use in our daily lives as well as for industrial applications. Consumer products that we use and interact with every day are not only continuously getting smaller, but also are loaded with more integrated multi-functionalities. Similar trends have also taken place in other devices such as portable and distributed power generation devices (batteries, fuel cells, micro-turbines), electronic cooling systems, medical devices (pace makers, catheters, stents), sensors, etc. As a consequence, components for such devices and systems also get smaller down to micro/meso-scales, with a near future expectation into nano-scales. Micro-fabrication techniques for silicon materials have been well established and utilized in manufacturing of micro-electronics devices. There have been hundreds, if not thousands, of books written about semiconductors, micro-electronics and related micro-fabrication processes. Hence, their adaptation is apparent for systems such as Micro-Electromechanical-Systems (MEMS) for use in aforementioned miniature devices and products. However, these techniques are mostly limited to silicon as a starting material. When complex and integrated products are required, for cost effective design and use of metallic components, thus far, well-known macro-fabrication methods such as forming and machining were adapted into micro/meso-scales mainly using intuition and experience.

In this work, a collection of esteemed authors from a broad range of backgrounds and institutions worldwide has prepared, possibly one of the first extensive books on micro-manufacturing processes for mainly non-silicon materials. The main goal was to gather the experience, technological know-how and scientific findings in a wide variety of topics and applications in a synergistic and coherent book for the benefit of students, researchers, engineers, managers and teachers who would start their investigations studies, preparations or careers with a concise set of information.

The first chapter, written by Drs. M. Koç and T. Özel, summarizes the recent developments and findings on micro-manufacturing, including the size effects, applications, tooling, etc., reported in the literature with examples and applications. In the second chapter, prepared by Dr. K. Teker, a summary of well-known micro-fabrication methods for silicon materials is presented to allow readers to compare them with the processes described in the rest of the book. The third chapter, which is prepared by Drs. T. Makino and K. Dohda, describes the issues in modeling and analysis for micro-manufacturing processes along with a comparison of different modeling approaches. Drs. O. Karhade and T. Kurfess present metrology, inspection and quality control aspects at micro-scales, and describe alternative methods to do so. Dr. A. Bandyophadyay and his colleagues discuss micro-layered manufacturing processes to be used for medical devices, sensors, etc. made out of metals and plastics in Chapter 5. In Chapter 6, Dr. Wu and Dr. Özel describe some of the micro-manufacturing processes based on laser processing with several examples and discuss long and short pulsed laser-material interactions. Micro Injection Molding process for polymers is presented by Dr. Yao in Chapter 7 while Micro-mechanical Machining is introduced in Chapter 8 by Dr. Özel and his associate. Dr. Koç prepared Chapter 9 with his colleague Dr. Mahabunphachai on micro-forming processes such as micro-forging, micro-stamping, micro-hydroforming and size effects. Dr. Rahman and his group cover in Chapter 10 micro-EDM processes including descriptions of equipment development. Dr. Fu Gang explains the micro Metal Injection Molding process in Chapter 11 with several examples of applications.

We would like to thank all of the authors who contributed to this book. We also extend our thanks to Ms. Anita Lekhwani of John Wiley who assisted us in all stages of preparing this book for the publication.

MUAMMER KOÇ and TUĞRUL ÖZEL
June 2010

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CONTENTS

CHAPTER 1

FUNDAMENTALS OF MICRO-MANUFACTURING

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1.1 INTRODUCTION

During the last decade, there has been a continuing trend of compact, integrated and smaller products such as (i) consumer electronics—cell phones, PDAs (personal digital assistant), etc.; (ii) micro- and distributed power generators, turbines, fuel cells, heat exchangers [1–4]; (iii) micro-components/features for medical screening and diagnostic chips, controlled drug delivery and cell therapy devices, biochemical sensors, Lab-on-chip systems, stents, etc. [5–8]; (iv) micro-aerial vehicles (MAV) and micro-robots [9–12]; and (v) sensor and actuators [13,14] (Fig. 1.1). This trend requires miniaturization of components from meso- to micro-levels. Currently, micro-electromechanical systems (MEMS), mostly limited to silicon, are widely researched and used for miniaturized systems and components using layered manufacturing techniques such as etching, photolithography, and electrochemical deposition [15,16]. Such techniques are heavily dependent on technologies and processes originally developed for micro-electronics manufacturing. However, MEMS have some limitations and drawbacks in terms of (i) material types (limited to silicon in combination with sputtered and etched thin metallic coatings), (ii) component geometries (limited to 2D and 2.5D), (iii) performance requirements (i.e., types of mechanical motions that can be realized, durability, and strength), and

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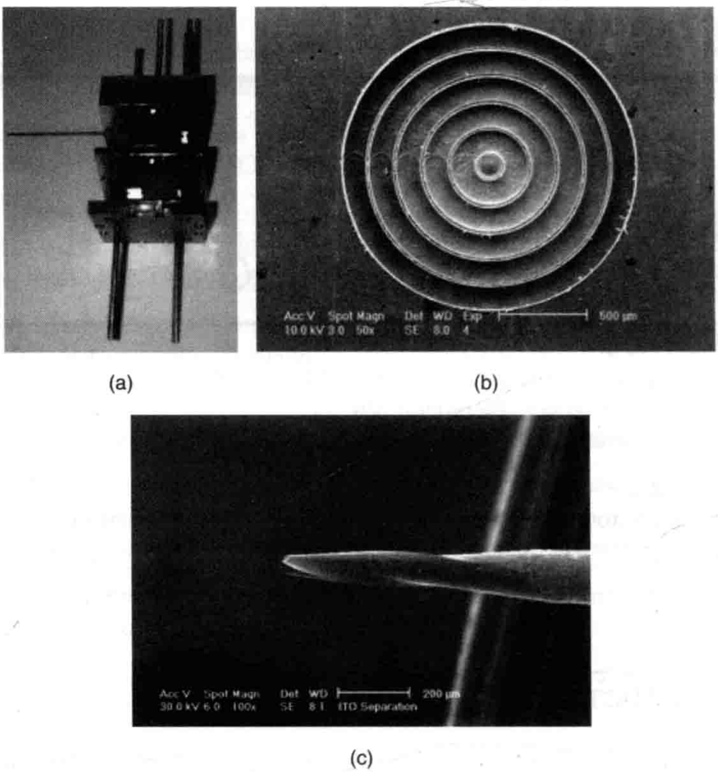
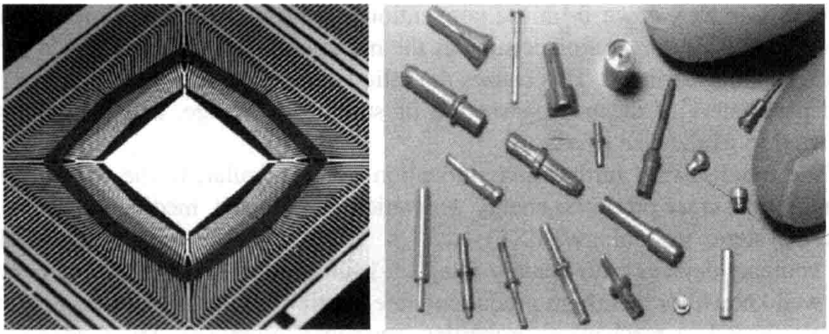


Figure 1.1 (a) Micro-channel chemical reactor, components are manufactured by laser micro-machining [20]; (b) pattern of concentric 127 μm channels of varying depth up to 125 μm cut into a brass workpiece; (c) SEM photograph of the front view of the 127 μm diameter two-flute end mill [21].

(iv) cost (due to slow and sequential nature of processes that are not amenable to mass production).

These issues lead the way for researchers to seek alternative ways of producing 3D micro-components with desired durability, strength, surface finish, and cost levels using metallic alloys and composites. Micro-machining processes have been widely used and researched for this purpose [15–17]. For instance, the laser micro-machining is used to fabricate micro-structures (channels, holes, patterns) as small as 5 μm in plastics, metals, semiconductors, glasses, and ceramics. Aspect ratios of 10:1 are claimed to be possible with this process. As a result, micro-scale heat exchangers, micro-membranes, micro-chemical-sensors and micro-scale molds can be fabricated with micro-machining. However, these processes are not appropriate for high-volume-low-cost applications [18,19]. Figure 1.2 depicts representative parts and features manufactured using mechanical micro-machining process.

As an alternative, micro-forming (micro-extrusion, micro-embossing, micro-stamping, micro-forging, etc.) processes have been considered and researched



(a) (b)

Figure 1.2 (a) lead frame (pitch 300 μm) blanks stamped for electronic connectors [19]; (b) Sample micro-extruded/forged parts.

as a prominent processing method because of their potential capabilities to produce a large volume of components cost-effectively [19,22–25]. Examples of micro-extruded parts are shown in Fig. 1.2. Micro-forming poses some difficulties because of the size and frictional effects associated with material forming processing. For micro-components in the ranges of interest (0.1–5 mm), the surface area/volume ratio is large, and surface forces play important roles. As the ratio of feature size to grain size becomes smaller, deformation characteristics change abruptly with large variations in the response of material [26]. Thus, new concepts are needed to extend forming processes to micro-levels. Early research attempts indicate that micro-forming is feasible but fundamental understanding of material, deformation, and tribological behavior in micro-/meso-scale is necessary for successful industrialization of micro-forming [24,27].

The development of novel methods and use of alternative instruments for accurate and cost-effective measurement of material properties are needed in micro-forming process and tool and product design. As is well known, both solids and fluids exhibit different properties at the micro-scopic scale. As the size scale is reduced, surface and size effects begin to dominate material response and behavior. Consequently, material properties obtained on regular scale specimens are no longer valid for accurate analysis and further design. Mechanical, tribological, and deformation properties deviate from bulk values as the characteristic size of the micro-components approaches the size scale of a micro-structure, such as the grain size in polycrystalline materials [22,27]. The ultimate challenge and the fundamental underlying barrier in the advancement of micro-forming processes are to be able to characterize these properties at the micro-scale in an accurate and reasonably cost-effective manner.

1.2 MICRO-FORMING (MICRO-SCALE DEFORMATION PROCESSES)

Micro-forming is defined as the production of metallic parts by forming with at least two part dimensions in the submillimeter range [27]. When a forming process is scaled down from the conventional scale to the submillimeter range, some aspects of the workpiece such as the micro-structure and the surface topology, remain unchanged. This causes the ratio between the dimensions of the part and parameters of the micro-structure or surface to change, and is commonly referred to as the *size effects*.

The trend toward further miniaturization—in particular, in the field of electronics, consumer products, energy generation and storage, medical devices, and micro-systems technology (MST)—will persist as long as consumers still seek for compact devices with heavily integrated functions. Metal forming processes are well known for their high production rate, minimized material waste, near-net-shapes, excellent mechanical properties, and close tolerances. These advantages make metal forming suitable for manufacturing of micro-features, especially where a high-volume-low-cost production is desired [19,28]. However, the well-established metal forming technology at the macro-scale cannot be simply applied in the micro-levels due to the so-called "size effects" on the material behavior. At the micro-level, the processes are characterized by only a few grains located in the deformed area; thus, the material can no longer be considered as a homogeneous continuum. Instead, the material flow is controlled by individual grains, that is, by their size and orientation [29]. As a result, conventional material properties are no longer valid for accurate analysis at this level. Furthermore, the deformation mechanism changes abruptly with large variations in the response of material as the ratio of grain size to the feature size decreases. Surface interaction and friction force become more prominent as the ratio of the surface area to volume increases [26,28]. These issues have been investigated to better understand, define, and model the "size effects." Additional size effects concerning the forming process are forming forces, spring-back, friction, and scatter of the results.

A micro-forming system comprises five major elements: material, process, tooling, machine/equipment, and product as illustrated in Fig. 1.3. The size effect is a dominant factor in design, selection, operation, and maintenance of all these elements. For example, a major problem in micro-forming lies in the design and manufacturing of the tools (i.e., dies, inserts, and molds). Small and complex geometries needed for the tools are difficult to achieve, especially when close tolerances and good surface quality are desired. Special tool manufacturing techniques are required to overcome these difficulties. Carefully selected tool material and simple shaped/modular tools can help reduce the cost of tool making and the degree of difficulty regarding the tool manufacturing, and increase tool life.

A vital challenge for micro-machine and equipment is the required precision at a high-speed production. In general, positioning of the micro-parts during the production process requires an accuracy of a few micrometers to submicrometers depending on the part type and ultimate use. In addition, as the part size is extremely small and the part weight is too low, handling and holding of micro-parts becomes very difficult due to adhesive forces (van der Waals, electrostatic, and surface tension). Therefore, special handling and work holding equipment need to be developed to overcome these difficulties in placing, positioning, and assembling the micro-parts. Also, clearance or backlash, between a die and a

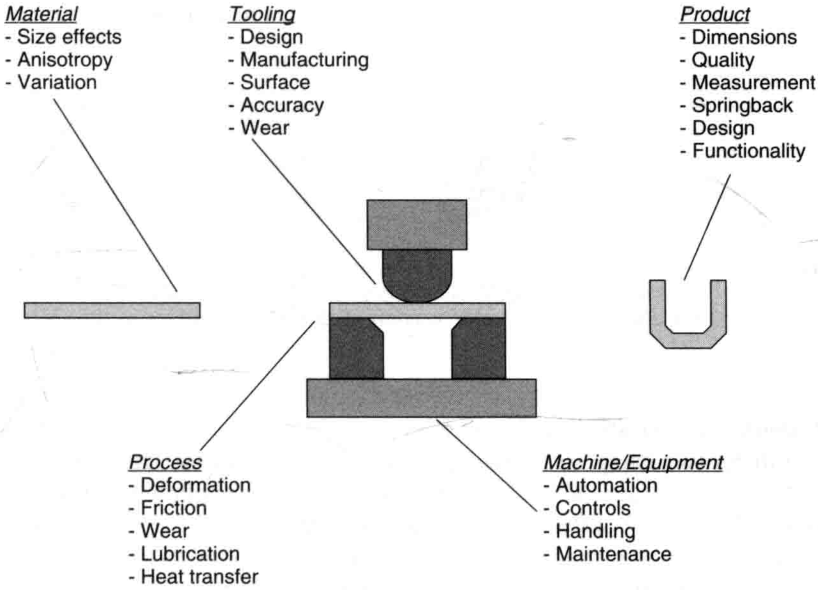


Figure 1.3 Micro-forming system.

punch that could be negligible at the conventional scale, can be a problem when the total required stroke to form the micro-part and clearance lies in the range of a few hundred micrometers [27]. Another challenge concerns the accurate measurement, inspection, and monitoring system of the process and dimensional parameters during and after the forming process. Automation systems for the micro-manufacturing are another issue that will eventually need to be studied and improved for the high-volume-low-cost production process.

1.2.1 Size Effects in Micro-forming Processes

For the accurate analysis and design of micro-forming processes, proper modeling of the material behavior at the micro-/meso-scale is necessary by considering the size effects. Two size effects are known to exist in metallic materials. One is the "grain size" effect and the other is the "feature/specimen size" effect (see Figure 1.4). The former is generally represented by the Hall–Petch law, which states that the material strengthens as the grain size decreases. The latter is observed when the miniaturization of the part occurs resulting in the decrease of the flow stress. Although the first studies on "feature/specimen size" effect were as early as the 1960s, up until now, no models quantitatively describe the phenomena. In order to implement the miniaturization effect into simulation tools, a quantitative description of the phenomena is necessary. In this chapter, an attempt has been made to quantify the size effect on the flow stress by considering the fundamental properties of single and polycrystal plasticity.

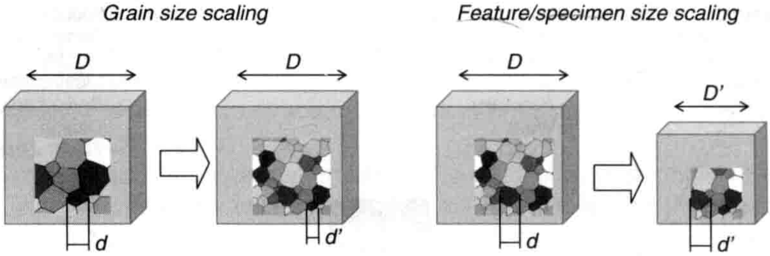


Figure 1.4 Illustration of two types of scaling effects: "grain size effect" and "feature/specimen size effect." (A full color version of this figure appears in the color plate section.)

According to Armstrong [30] and Kim *et al.* [31], the size effects can be investigated under two categories—the "grain size effect" and the "feature/specimen size effect." The "grain size effect" has been known to follow the Hall–Petch equation [32,33]. This effect purely depends on the average size of the material grains and is the dominant effect on the material response at the macro-levels. However, as the feature/specimen size reduces to the micro-scales, the "feature/specimen size effect" has also been reported to have considerable impact on the material response, and thus manufacturability.

Depending on the material testing methods or metal forming processes, the "feature/specimen size effect" could be further divided into two distinctive effects: the "feature size effect" and the "specimen size effect." In general, the "specimen size" can be referred to as the diameter of a billet (rod) or the thickness of a blank (sheet) to be tested or formed, while the "feature size" could be regarded as the smallest feature (channels, radii, protrusions, etc.) on the final part that these specimens will be formed into. For example, in an extrusion process of micro-pins, the specimen size would be the initial diameter of the rod/billet, while the feature size would be the diameter of the reduced section. In the case of micro-channels formed on an initially flat thin sheet blank, specimen size will be regarded as the thickness of the blank, while micro-channels will be the feature of interest and their dimensions (i.e., width and height) will represent the feature size. Similarly, in a bulge test of thin sheet blank, the specimen size will be the blank thickness, while the feature size will be the bulge diameter. With this distinction between the specimen size and the feature size effects, it is obvious that a tensile test could be used only to study the effect of the specimen size but not the feature size on the material behavior.

Even though these size effects can be distinguished based on the above discussion, as the grain, specimen, and feature sizes get smaller and smaller into the micro-scales, their effects are coupled, and therefore should be considered together. Koç and Mahabunphachai [34] proposed the use of two characteristic parameters N and M to couple and represent these interactive effects, where N is defined as the ratio between the specimen and the grain sizes, and M is the ratio between the feature and the specimen sizes. By defining N and M, all

TABLE 1.1 Type of Size Effects and Characteristic Parameters

	Size Effects		
	Grain Size	Specimen Size	Feature Size
Tensile test	d	t_0, D_0	—
Bulge test	d	t_0	D_c
Stamping process	d	t_0	D_c
Extrusion process	d	D_0	D_c
Characteristic parameter	$N = t_0/d$ or D_0/d		$M = D_c/t_0$ or D_c/D_0

combinations of the interactive effects, that is, grain-to-specimen, specimen-to-feature, and grain-to-feature sizes, can be represented and quantified using N, M, and $N \times M$, respectively. A summary of different types of size effects and their corresponding characteristic parameters is presented in Table 1.1, where d is material grain size, t_0 the specimen thickness, D_0 the specimen diameter, and D_c the die cavity.

The "specimen size effect" (t_0 or D_0) on the material flow curve as a measure of material response was observed in various tensile test conditions for a variety of materials such as CuAl alloy [35], CuNi18Zn20, CuZn15 [36], CuZn36 [37], and aluminum [38,39]. While the grain size shows a strong effect on the material response at all length scales (i.e., from macro- to micro-scale), it is not until the N value is around 10–15 that the "specimen size effect" starts to influence the material response [31,38,40]. In general, the tensile test results showed a decreasing trend of the flow stress with the decreasing specimen size (i.e., decreasing N value) as illustrated in Fig. 1.5a and 1.5b. Similar observations were reported in upsetting tests of copper, CuZn15, and CuSn6 [19] as illustrated in Fig. 1.5c, and in bulging test of CuZn36 [37] as illustrated in Fig. 1.5d. This trend of decreasing flow stress with decreasing N value was rather consistent based on the results of various studies. However, as N is reduced close to a range of 2–4, several researchers had reported an increase in the flow stress as N is decreased further. For instance, the tensile test results of 99.999% Al rods by Hansen [38] showed an increase in the flow stress as N decreases from 3.9 to 3.2 (Fig. 1.5a). Similar results were also observed in micro-/meso-scale hydraulic bulge testing of thin CuZn36 blanks [37], where the flow stress was found to increase as N value decreases from 5 to 3.3 ($d = 60$ μm, t_0 reduced from 0.3 to 0.2 mm) as shown in Fig. 1.5. An increase in the flow stress was also observed as N is reduced close to 1 (single crystal deformation) as reported in bending tests of CuZn15 and aluminum 99.0–99.5% [36,39]. Nevertheless, in the tensile test results of CuNi18Zn20 specimens by Kals and Eckstein [36], a continuous decrease in the flow stress was reported as N decreased from 25 to 2.5 (i.e., $d = 40$ μm, $t_0 = 1.0$, 0.5, and 0.1 mm) as shown in Fig. 1.5b. A summary of the effect of N on the flow stress based on the findings reported in the literature is presented in Fig. 1.6.

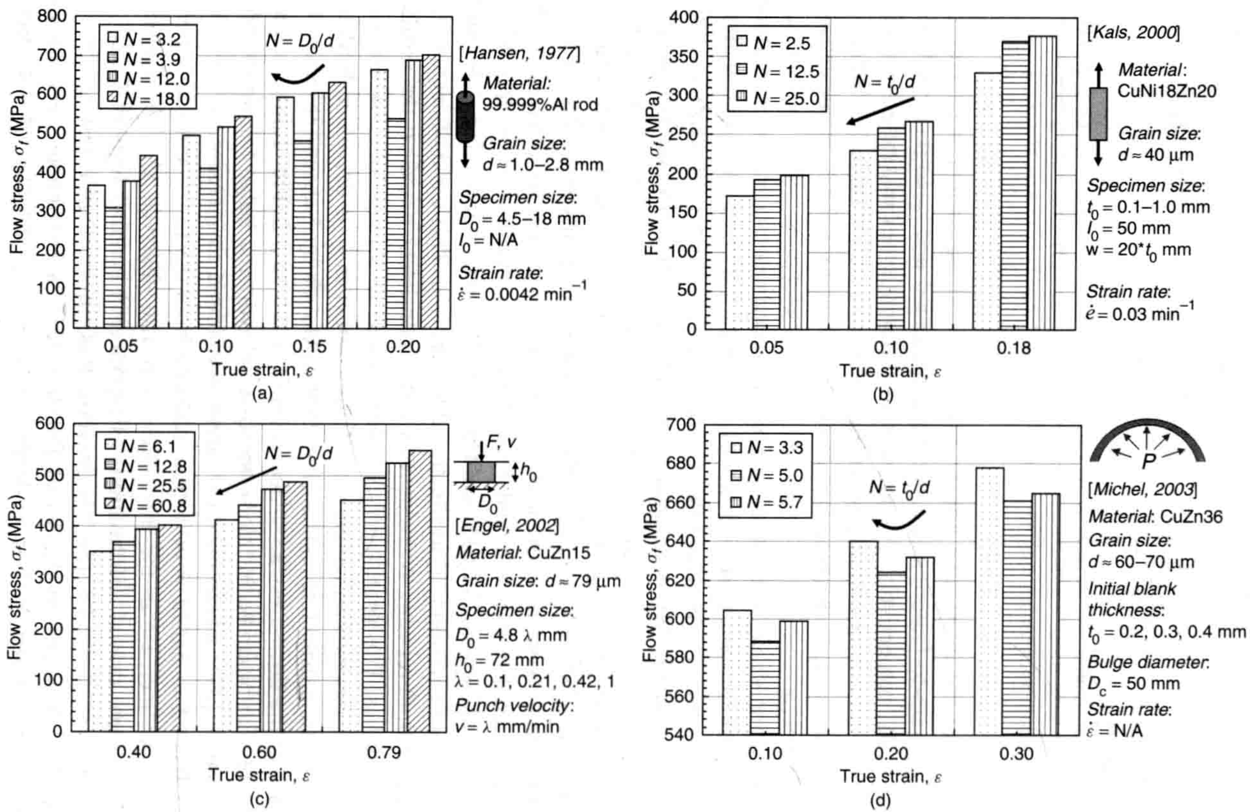


Figure 1.5 Effect of N on material flow stress under different testing conditions.