Ultrasonic nondestructive characterization of metallurgical reactions

Caractérisation ultrasonore non destructive concernant des réactions métallurgiques

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Dr. Rosen has been engaged in studies of the elastic, anelastic and magnetoelastic behavior of lanthanides and actinides near first and second order phase transitions, precipitation processes in alloys, relaxation and crystallization phenomena in amorphous systems, and in the general field of nondestructive characterization, employing ultrasonics, acoustic emission and eddy currents techniques. Recently he developed and applied noncontact techniques for laser generation and interferometric detection of acoustic waves in ribbons, thin foils and microstructurally modified surface layers. M. Rosen published about 120 papers in journals such as Physical Review, Physics and Chemistry of Solids, Philosophical Magazine, Materials Science and Engineering, Acta and Scripta Metallurgica.

SUMMARY

Development and application of novel ultrasonic methodologies employing both semicontact (piezoelectric detection) and noncontact (laser generation and laser interferometric detection) for dynamic characterization of crystallization processes in melt-spun metallic glasses, is discussed. The behavior of the elastic moduli, determined ultrasonically, were found to be sensitive to relaxation, crystallization and phase decomposition phenomena in rapidly solidified metallic glasses. Analytical ultrasonics enables determination of the activation energies and growth parameters of the reactions. Therefrom theoretical models can be constructed to explain the changes in mechanical and physical properties upon heat treatment of glassy alloys. The composition dependence of the elastic moduli in amorphous Cu−Zr alloys was found to be related to the glass transition temperature, and consequently to the glass forming ability of these alloys. Dynamic ultrasonic analysis was found to be feasible for on-line, real-time, monitoring of metallurgical processes. A second part of this review presents experimental evidence for the characterization of laser and electron-beam modified surface layers. By means of determination of the Rayleigh surface waves velocities as a function of frequency both the nature and the thickness of the modified surface layer could be nondestructively evaluated and analyzed.

KEY WORDS

Ultrasonics, nondestructive characterization, elastic moduli, noncontact testing, laser, thermoelastic generation, interferometric detection, surface modification, Rayleigh waves, metallic glasses, amorphous alloys.

RÉSUMÉ

Nous décrivons le développement et l'application de méthodologies nouvelles qui utilisent des méthodes à semi-contact (détection piezoélectrique) et à non-contact (génération par laser et détection interférométrique de laser) pour la caractérisation dynamique des processus de cristallisation dans des rubans de verre métalliques. Le comportement des modules d'élasticité déterminé par méthodes ultrasonore est sensible aux phénomènes de relaxation, cristallisation et décomposition de phases dans les verres métalliques rapidement refroidis. L'analyse ultrasonore permet la détermination des énergies d'activation et des paramètres du grossissement des réactions. A la base de ces résultats il a été possible de mettre au point des modèles théoriques permettant d'expliquer les changements des propriétés mécaniques et physiques survenant à la suite du traitement thermique des verres métalliques. La variation des modules d'élasticité en fonction de la décomposition dans les verres métalliques Cu–Zr est liée à la température de transition de verre et par conséquence à leur tendance à former des verres. L'analyse dynamique ultrasonore permet le contrôle « on-line » et en temps réel des processus métallurgiques. La seconde partie de cette synthèse met en évidence l'expérience sur lă caractérisation des couches superficielles qui avaient été modifiées par irradiation au faisceaux de laser ou d'électrons. Par détermination de la vitesse des ondes de surface de type Rayleigh en fonction de la fréquence on a pu évaluer et analyser de façon non destructive aussi bien la nature que l'épaisseur de ces couches superficielles.

MOTS CLÉS

Ultrasonore, caractérisation non destructive, modules d'élasticité, essai sans contact, laser, génération thermoélastique, détection interférométrique, modification de surfaces, ondes de Rayleigh, verres métalliques, alliages amorphes.

CONTENTS

1. Introduction

Ultrasonic nondestructive evaluation has traditionally been concerned with the search and location of flaws in materials structures and the determination of their distribution and orientation. A considerable body of knowledge has also been accumulated from ultrasonic scattering studies in assessing grain size and orientation effects in materials. Recently, it has become widely recognized that ultrasonic measureemnts can be used to characterize materials structures and hence properties such as strength, toughness, effect of residual stresses so as to supplement, or even replace, the conventional destructive techniques employed in metallurgy. Ultrasonic nondestructive characterization offers distinct advantages in that materials properties can be verified on actual components of engineering structures. The scientific literature is extremely scarce in dynamic nondestructive characterization (NDC) whereby ultrasonic techniques are applied to on-line, real-time, monitoring of microstructures for the control of metallurgical processes. Inherent difficulties related to these types of measurement methodologies include operation at elevated temperatures and in hostile environments. Furthermore, there are little basic data available on the relationship between the metallurgical microstructures and measured ultrasonic responses. Therefore, the full potential of ultrasonic techniques in this field is yet to be realized.

Recent studies have addressed the specific area of dynamic, real-time nondestructive characterization of metallurgical microstructures, e. g., precipitation hardening of aluminium alloys and crystallization of amorphous alloys [1-4]. Conventional bulk ultrasonic techniques were adapted for application to continuously monitor changes of the microstructure and the effect on physical properties. However, the growing interest in metallic glasses has created the need for the determination of their physical and mechanical properties. Some of these properties, especially the mechanical ones, cannot be measured conveniently by traditional ultrasonic methods as the high cooling rates required to form metallic glasses restrict their physical shapes to shallow layers or thin ribbons. Alternate measurement methodology needed to be developed in order to accurately assess these properties. One of the techniques employs a coil to magnetostrictively launch and detect extensional waves in a ribbon or magnetic material, called the "driver". The specimen can be coupled to the end of the driver, producing an echo pattern from which the extensional velocity in the material can be derived by a pulsesuperposition technique [5]. A pulser-receiver was constructed to feed high current pulses to the coil and to amplify the electrical signals produced in the coil by acoustic waves. In attempting to dynamically characterize metallurgical processes in amorphous ribbons or structurally modified thin surface layers, the conventional ultrasonic techniques were found to be inadequate. Thus, a new approach for contactless generation and detection of acoustic waves, using a laser generation and laser interferometric detection system, was developed [6].

2. Techniques for noncontact generation and detection of ultrasonic waves

The noncontact feature of both generation and detection of ultrasonic waves can be very advantageous in situations requiring physical separation between the measuring system and the material under investigation, for instance, when high temperatures or hostile atmospheres are involved. Furthermore, the contactless generation and detection precludes interaction with, and modification of, the wave propagation pattern under the study. In addition, laser generation of acoustic waves yields a wide variety of propagation modes (longitudinal, transverse and plates modes, Rayleigh waves) over a wide frequency range, thus enhancing the amount of information obtained from a single measurement.

Compressive stress waves that propagate in a material can be generated by transient loads applied by rapid energy transfer from a single-pulse-Q-switched high-energy Nd:YAG laser, (*fig.* 1). Propagation of ultrasonic waves in a medium causes surface displacements on the material that can be measured optically by exploiting the phase shift of an optical beam reflected from the surface of the material. When the reflected beam is combined with a reference optical beam, from a helium-neon laser, optical phase changes are converted into amplitude phase changes that are detectable by a sensitive photodiode. These variations in amplitude are proportional to the surface displacements on the specimen. Potential problems arising from the fact that phase changes also result from relative motion among optical components of the system and from temperature and pressure fluctuations of the ambient air, are prevented by appropriate design of the interferometer. An optical scheme due to Fizeau is particularly suitable for our specific purpose. Two optical probes are separated to allow accurate measurements of travel time of an ultrasonic wave in the material over a well-defined distance. Furthermore, the variation in magnitude of the surface displacements detected by the two interferometers determines the ultrasonic attenuation in the material. Thus, both velocity and attenuation can be measured simultaneously (*fig.* 2). The interferometer was built at Johns Hopkins University by Dr. Harvey Palmer.

Compared with other sensors, optical interferometers offer several advantages. The sensitive area can be made very small, a few micrometers in diameter, for highly localized measurements. Consequently, the surface of the specimen does not necessarily have to be flat optically. The highly focused optical beams permit utilization of specimens with conventionally machined surfaces. The measured quantity is linear displacement. Independent methods of absolute calibration are applicable. Bandwidth, determining the fidelity of reproduction of signal waveforms, is not limited by the character of the transduction process but by the electronics of the interferometer detectors. Therefore, performance can largely exceed that of conventional piezoelectric transducers. Small signal resoluton and bandwidth are related, thus linear displacements of a few angstroms are detectable at 7 MHz bandwidth.

Laser pulse irradiation produces a stress pulse of short duration (15 ns) and relatively high amplitude (up to 200 mJ power) making the investigation of very thin (about 20 µm) and highly attenuating specimens

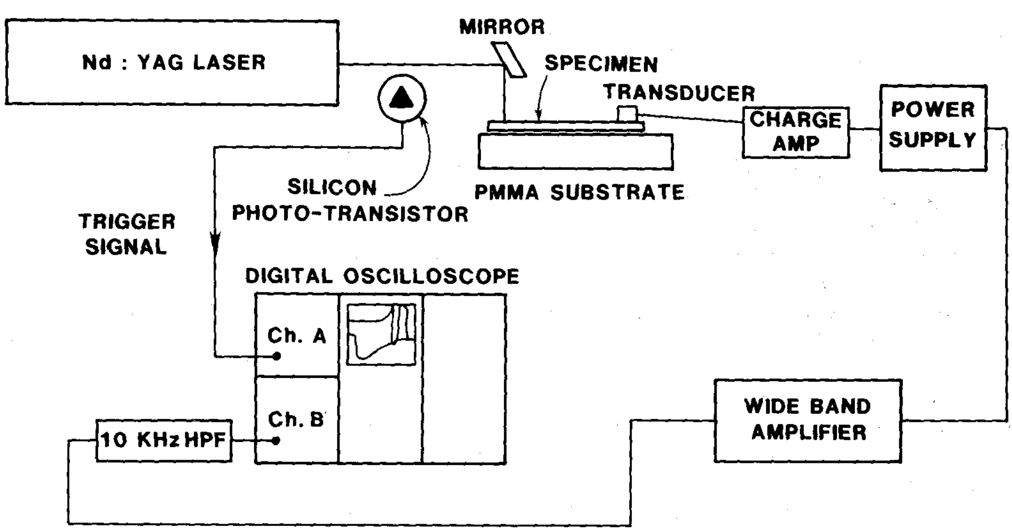

Fig. 1. — Sound velocity measurement system based on laser generation and piezoelectric detection of the propagating sound waves.

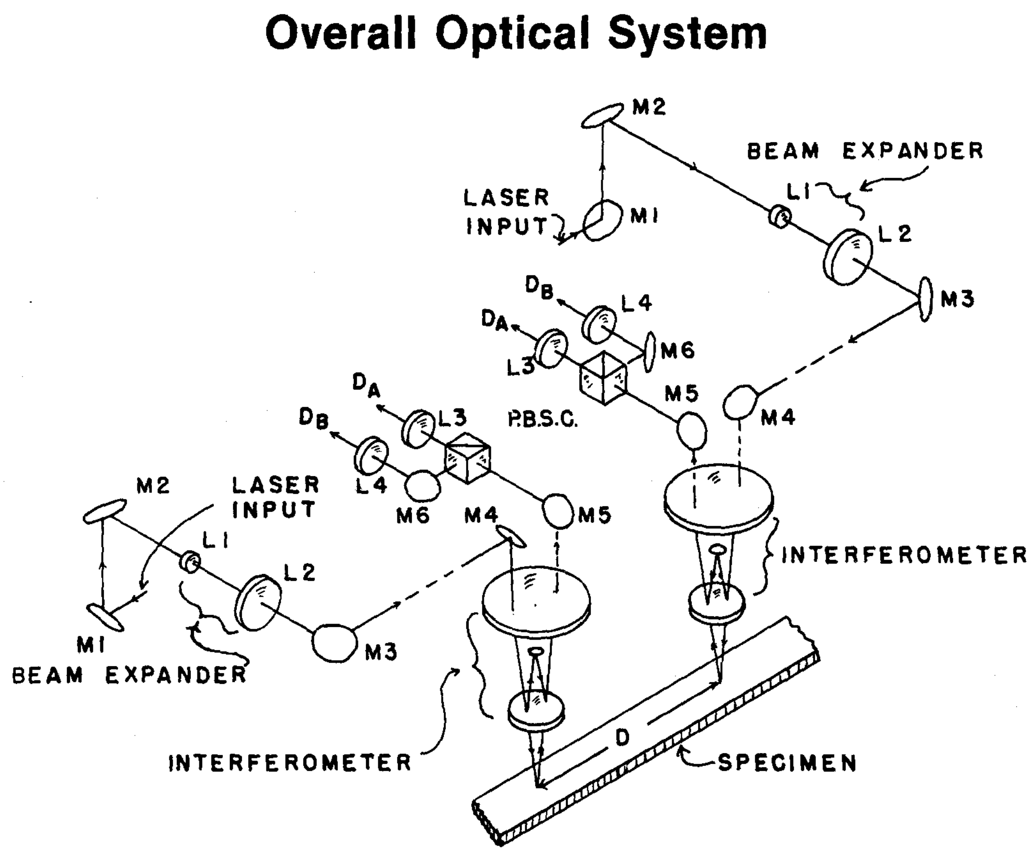

Fig. 2. — Dual laser interferometer (Fizeau).

possible. Since a multitude of acoustic wave propagation modes is generated the dual interferometer provides important information concerning the elastic and inelastic properties of the material under static or dynamic conditions.

The contactless generation and detection of acoustic waves is extremely advantageous because specimens can be studied while they are subjected to thermomechanical processing under adverse environmental conditions. No transducer protection (e.g., from elevated temperatures) is necessary, and the detected ultrasonic waveform is unperturbed by extraneous effects due to physical contact between specimen and transducer. Data acquisition is straightforward and real-time or post-test analysis is feasible. The capability to obtain the frequency dependence of both sound velocity (in dispersive regimes) and ultrasonic attenuation offers new opportunities in solid state and physical metallurgy research where the elastic properties and acoustic energy absorption play a prominent role in the characterization of the processes.

Laser and electron beam irradiation techniques are being extensively applied for the modification of surface properties of metallic structures [7, 8]. The nature of the modified surface zones is not amenable to conventional nondestructive characterization. However, the analysis of Rayleigh wave velocities, and the determination of the elastic moduli, may lead to a better understanding of the properties of the modified surface layers. Laser or piezoelectrically generated Rayleigh surface waves probe preferentially the near-surface region of the sample, and are extremely sensitive to variations in the elastic properties and ultrasonic attenuation of the material medium. The extent of penetration of the Rayleigh surface wave normal to the surface of the sample depends on the frequency of the propagating Rayleigh waves and the exponential decay of their intensity. For a typical metallic phase, the Rayleigh wave velocity, V, is about 3,000 ms^{-1}. For a frequency of 10 MHz, the Rayleigh wavelength is, therefore, 300 μm. Theory shows that 90 percent of the energy of the Rayleigh wave is contained within one wavelength from the surface. Thus, the sub-surface region can be monitored with a high degree of accuracy. Moreover, Fourier analysis of the frequency content of the Rayleigh waves, when the dual-laser interferometer is used to contactlessly detect the propagating surface waves, allows the precise determination of the thickness of the surface layer. This gauging procedure is possible because of the unique property of the Rayleigh wave velocity that is independent of frequency.

Two properties of the Rayleigh surface wave make its detection possible by optical means. One, is the surface microcorrugation (microdistortions) as the Rayleigh wave propagates through the material medium. Second, is the periodic variation of the index of refraction while the wave propagates on the surface. By means of optical interferometry, e. g., dual Fizeau interferometer, these waves can easily be detected in a contactless fashion. Thus, the contactless generation and detection of Rayleigh waves enables one to dynamically study the near-surface modifications of the material while the samples are contained in a hostile environment, and are subjected to programmed thermomechanical treatments subsequent to laser or electron beam alloying and microstructural modification.

3. Nondestructive characterization of crystallization processes in metallic glasses

Amorphous alloys, or glassy metals, are solids with frozen-in liquid structures. The absence of translational periodicity in the amorphous state along with the macroscopic compositional homogeneity are the main reasons for their improved properties, e. g., high mechanical strength, good corrosion resistance, and excellent magnetic behavior. Their unusual mechanical, chemical, and physical properties have stimulated extensive scientific and technological interest. One serious problem in the processing and utilization of amorphous alloys that may limit their future technological applications is their low thermal stability. When thermomechanical conditions are appropriate, metallic glasses relax structurally and ultimately crystallize into more stable structures resulting in drastic variation in properties. The factors governing the thermal stability of these alloys and their effect on properties are not well understood. For example, upon crystallization, amorphous alloys undergo very large changes in the elastic (4 percent) and anelastic properties with accompanying reduction in plastic properties (embrittlement). For this reason, availability of a nondestructive ultrasonic characterization technique for both property determination and metallurgical process control can be extremely useful.

Formation of metallic glasses through rapid solidification techniques and their subsequent crystallization upon heating has been the subject of numerous investigations. Characterization of the range of microstructures thus produced, using nondestructive techniques, is an attractive proposition both in terms of its contribution to the understanding of the kinetic phenomena at play during the various transformations, as well as its ultimate commercial utilization for on-line feedgack control of process variables.

Metallic glasses are not thermodynamically stable, and they tend to structurally relax and finally crystallize upon appropriate heat treatment. Waseda *et al.* [9] showed that annealing metallic glasses increased the short-range order. Egami [10] used energy-dispersive methods to confirm the log-time kinetics of the relaxation process. His work indicated that the activation energy for relaxation continuously increased with time, which may correspond to the removal of quenched-in defects. The process of crystallization into a stable state involves drastic variations in the properties of the material. Although changes in density and electronic structure associated with the crystallization process are rather minute [11], appreciable variations were observed in several physical properties, including the elastic moduli [12, 14]. The crystallization behavior of metallic glasses was examined by several workers [15-18]. It was found that small additions of noble metals (Cu, Ag) to Pd-Si greatly stabilizes the amorphous phase, and particularly in $Pd_{0.775}Cu_{0.06}Si_{0.165}$ glass [19] which became the subject of numerous investigations. The effect of isothermal annealing on the crystallization kinetics of $Pd_{0.775}Cu_{0.06}Si_{0.165}$ was determined by differential scanning calorimetry [19].

Associated with relaxation and crystallization of metallic glasses are variations in the elastic and mechanical properties. Young's modulus E and shear stiffness generally increase by 20-40 percent, but the bulk modulus K increases by only about 7 percent upon crystallization [13]. Kursomovic and Scott [20] found that E for $Cu_{60}Zr_{40}$ increased by about 10 percent due to structural relaxation and another 15 percent upon crystallization. In contrast, the density of glassy metals generally changes by only 0.3-1.5 percent.

Straightforward elasticity and wave propagation theories enable one to calculate E [21]. For one-dimensional extensional wave propagation in a homogeneous, isotropic, linearly elastic solid, Young's modulus is given by $E = V_E^2 . \rho$ where v_E is the extensional wave velocity and ρ is density. Thus the velocity of the extensional waves had to be determined while the ribbons undergo specific heat treatments that induce the crystallization process.

The main objectives of the present investigation were as follows:

– Determination of the isothermal transformation kinetics from the amorphous to the crystalline state by means of monitoring changes in sound wave velocity (elastic modulus).

– Calculation of the kinetic parameters: activation energies and crystallite growth regime. Comparison with experimental evidence.

– Information about the relaxational changes occurring in the amorphous state, prior to crystallization.

– Corroboration with optical and electron microscopy, x-rays and microhardness concerning the relationship between microstructure and properties.

Metallic glass ribbons of PdCuSi and CuZr alloys were prepared by the melt spinning technique [12]. The samples were approximately 40 µm thick and 1.25 mm wide. Ultrasonic, x-ray, and metallographic examination prior to the crystallization treatment revealed no crystallinity. Crystallization was performed in evacuated quartz capsules at predetermined isothermal holding temperatures. Optical metallography indicated that the crystallization process in PuCuSi ribbons is not homogeneous in the bulk. Two coexisting growth processes were observed. Frontal growth from the free surfaces of the ribbon towards the inferior, and homogeneous nucleation and growth in the bulk.

The velocity of the ultrasonic extensional waves was determined by measuring the transit time of a single pulse generated by a laser and detected by a piezoelectric quartz-crystal transducer located at a distance of about 200 mm from the spot on the ribbon irradiated by the laser. The transient load was applied by rapid deposition of energy from a single-pulse of a Q-switched neodymium YAG laser with a wavelength pf 1.06 μm. The laser-pulse duration was 15 ns, and the pulse energy, for this specific series of measurements, was about 20 mJ. The laser pulse was line-shaped to produce a nearly plane wave. A photodetector was used to trigger a transient pulse recorder as the laser pulse was generated. Thus, the transit time of the extensional sound wave propagating along the ribbon could be determined to within better than 1 part in 10.

Figure 3 shows the variation of the extensional wave velocity, V_E as a function of crystallization time at three isothermal holding temperatures, 380, 390, and 400°C. The initial sound-wave velocity, in the amorphous state, was found to be 2,970 ms^{-1}, whereas in the fully crystallized state it reached an asymptotic value of 3,490 ms^{-1}. Taking 10.52 and 10.69 g cm^{-3} as the density of the amorphous and crystalline $Pd_{77.5}Cu_6Si_{16.5}$ respectively, the Young moduli could be calculated. They were found to be 9.46×10^3 kg.mm^{-2} for the amorphous state and 13.27×10^3 kg.mm^2 for the crystalline state, i. e., ΔE of about 40 percent. Figure 3 exhibits a relatively sharp increase in the sound velocity during the first five minutes of the isothermal holding. The variation of the extensional wave velocity with crystallization time manifests the dramatic changes in the elastic properties with an increase of about 40 percent in Young's modulus. The sigmoid curves represent the crystallization kinetics which are typical of a thermally activated process. Thus, the kinetic parameters, i. e., activation energy and the growth regime parameters can be determined from the NDC data [2, 3]. Furthermore, the time dependence of the crystallized volume fraction was found to be compatible with a diffusion controlled growth mechanism [23, 24] for a plane boundary growth that is preceded by a rapid nucleation process [25].

The effect of copper content on the Young's modulus of ZrCu alloys in the crystalline and amorphous state indicates that the lowest value of the Young's modulus is for pure crystalline zirconium, whereas the highest value is for pure crystalline copper (*fig.* 4). A maximum and a minimum are found for alloys with compositions near the intermetallic compounds

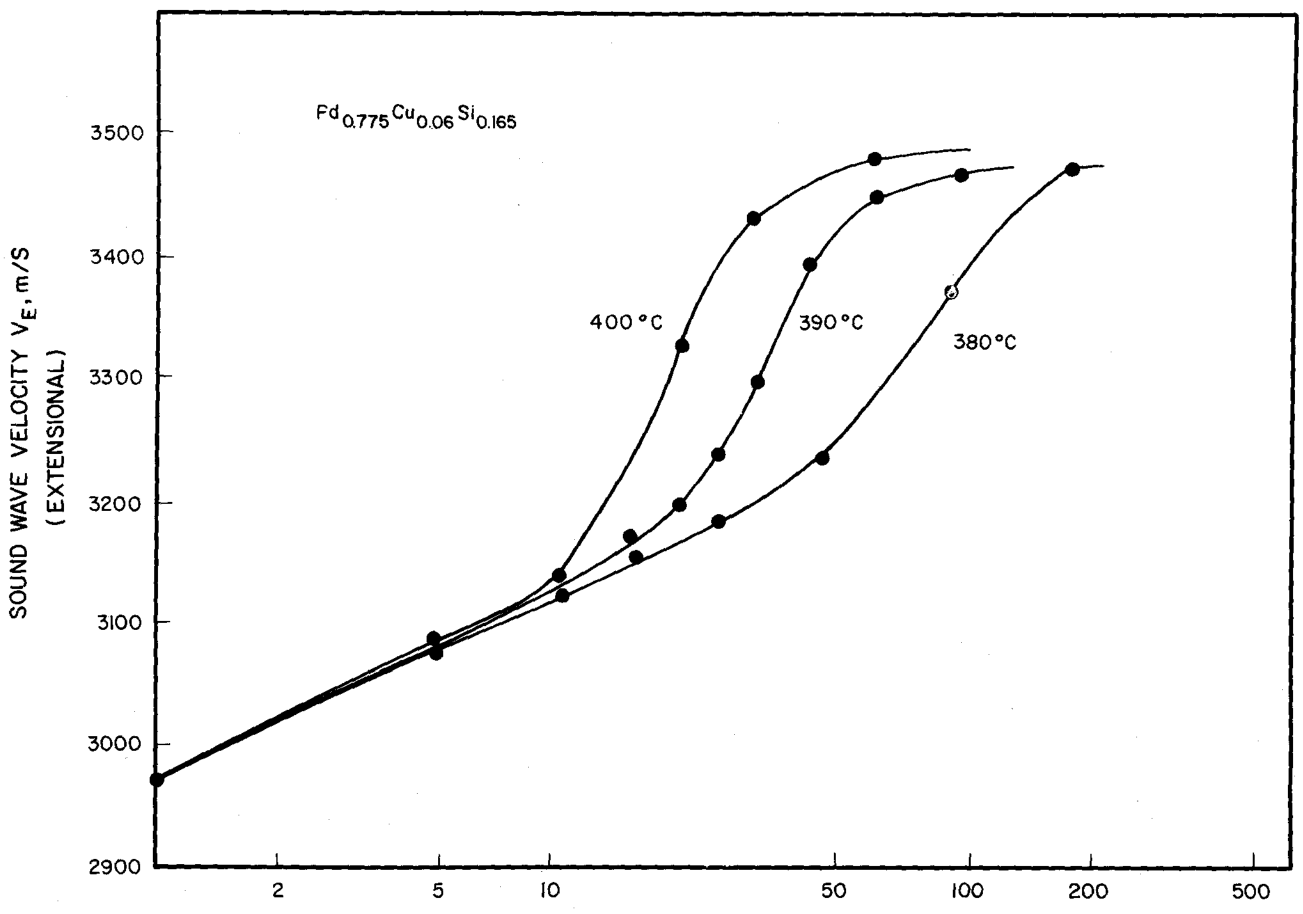

Fig. 3. — Variation of extensional wave velocity in PdCuSi during transition from amorphous to crystalline state as a function of crystallization time.

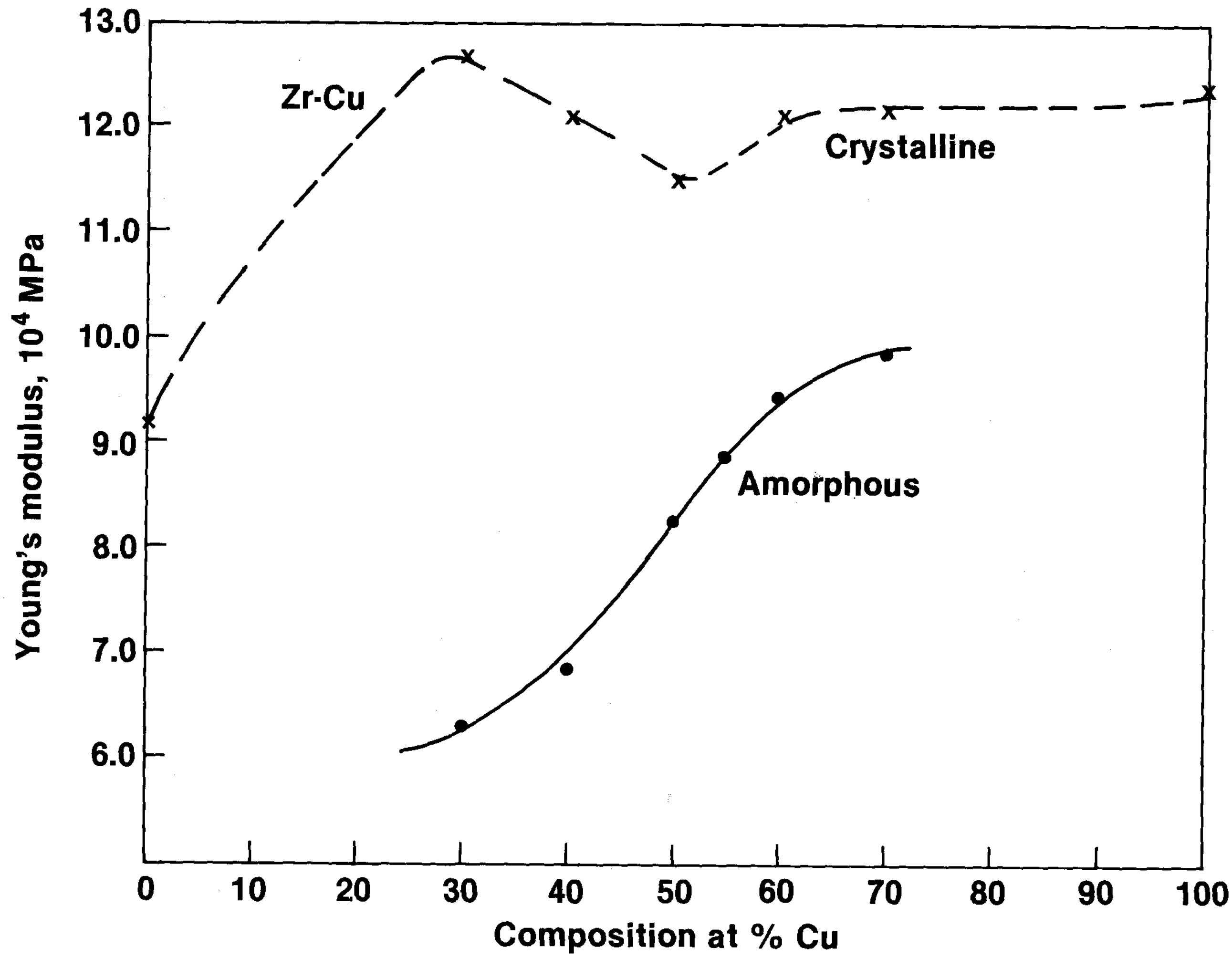

Fig. 4. — Variation of Young's modulus with copper content of amorphous and crystalline Zr-Cu alloys.

Zr_2Cu and ZrCu, respectively. The variations of the Young's with composition of the amorphous alloys, between 30 and 70 percent copper, is a smooth S-curve with an infection point at 50 a/o copper. It is conjectured that the amorphous state can be interpreted in terms of short range order structure where the mixing pairs Zr-Zr, Cu-Cu, and Cu-Zr are of equal probability at the composition of 50 a/o Cu. The inflection point on the Young's modulus versus composition curve will then represent the point for maximal configurational entropy of the metallic glass. Analysis of the temperature dependence of the sound wave velocity of Zr-Cu alloys in the composition range between 30 and 70 a/o Cu allowed determination of the activation energies of the diffusional processes governing the crystallization kinetics. The activation energy increases from 90 to 110 kcal/mole as copper content exceeds 50 a/o. The change in crystallization mechanism as copper content exceeds 50 a/o may be related to the configurational entropy change as the population of Cu-Cu pairs increases. The relationship between the behavior of the Young's modulus as a function of composition, and the variation of the activation energy of the crystallization process with copper content is yet to be elucidated. It is believed that this relationship is of basic importance in the understanding of the transformation of the amorphous state into coexisting compounds upon isothermal crystallization [4].

The initial increase in the extensional sound velocity, of about 3.7 percent, i. e., 7.4 percent in the Young's modulus of PdCuSi and a similar increase in the Zr-Cu amorphous alloys, appears to be related to a structural relaxation that precedes the crystallization process in the amorphous state [20, 24]. Structural relaxation was found to be particularly enhanced in glasses obtained at high quenching rates, where greater structural disorder is to be expected [26]. The lower elastic stiffness in the glassy state has been attributed to the interatomic displacements inherent in a disordered structure [27]. The elastic stiffness should, therefore, increase with increased local ordering as a consequence of the structural relaxation. Microhardness measurements on the ribbon edge, perpendicular to the length vector of the ribbon, revealed a dramatic increase in hardness while the material is still in the amorphous state, before crystallization ensues. The embrittlement mechanism is the amorphous alloy can be related to the removal of the quenched-in free volumes (vacancy clusters). Initially, the amorphous alloy has a disordered packing of the constituent atoms. The reduced coordination of the atom complexes, due to the presence of excess free volumes, allows shear transformations to be sustained. The free volumes are analogous to dislocation core segments. Consequently, the material is very ductile in the disordered amorphous state. Heat treatment in the amorphous region at temperatures below the glass transition temperature, Tg, or for relatively short periods of time at temperatures above Tg causes structural and compositional relaxation. The free volumes are redistributed by short range shuffling of the atoms, thus a more rigid close-packed atomic distribution of high coordination is achieved. The dense random packing of hard spheres (Bernal structure) leads to significant embrittlement of the amorphous phase.

The topological and compositional relaxation processes occurring in the amorphous state can be investigated by analyzing the behavior of the shear and compressional components of the ultrasonic attenuation, and their frequency dependence. From the frequency dependence of the ultrasonic attenuation, obtained by means of the dual-laser interferometer, the behavior of the bulk and shear viscosities can be characterized. Consequently, it is possible to establish the functional relationship between the appropriate relaxation times and the diffusional reactions leading to topological and compositional changes in the amorphous state. This specific phase of the investigation is currently in progress. It can be realized through the capability of the laser generation-laser interferometric detection of propagating sound waves, and the subsequent analysis of their frequency dependence within the framework of the viscoelastic theory.

4. Nondestructive characterization of microstructurally modified surface layers

High power lasers and electron beams have recently been applied for modifying metal surfaces and improving their physical, chemical, and mechanical properties [7, 8]. Modification of surface properties may involve incorporation of alloying elements into the surface layer or localized thermomechanical treatment leading to formation of microstructures of desired characteristics. The focused laser or electron beam energy is deposited in such a fashion as to melt a

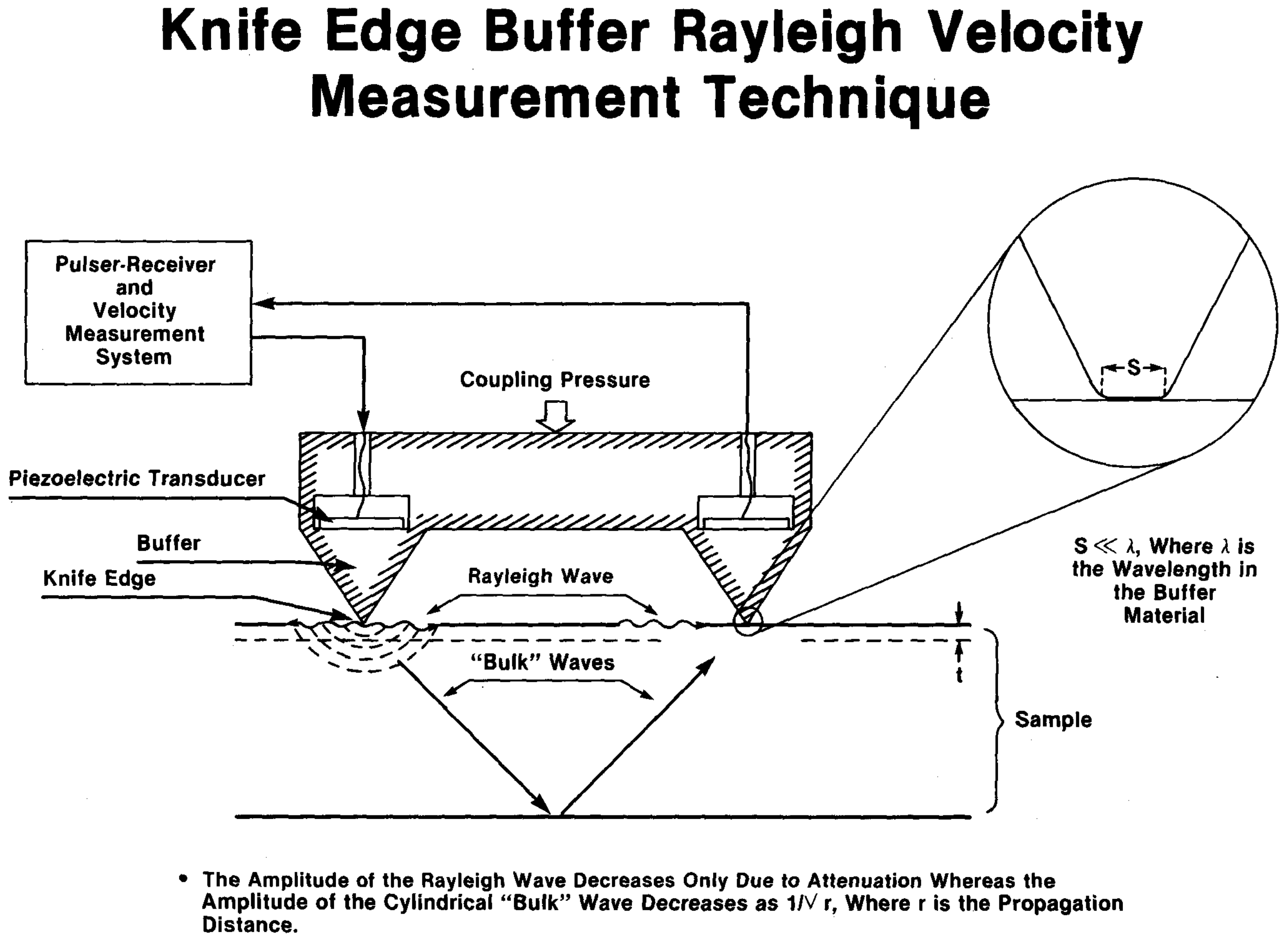

Fig. 5. — Rayleigh wave velocity measurements in microstructurally modified surface layers using the piezoelectric generation and detection technique by means of knife edge buffers.

thin layer while the bulk of the material provides the rapid quenching effect. Typical quenching rates may be of the order of 10^6 Ks^{-1} or higher. Control of the developing microstructures and their characterization is crucial to the understanding of the operating mechanisms responsible for the near-surface reactions and for the exploitation of the potential of this emerging technology for specific applications. Nondestructive characterization may be of prime importance for the on-line, real-time mechanical and physical evaluation of the surface properties, or as basic parameters for engineering design. Demands for safety and quality control have emphasized the lack of an acceptable NDE technique for quality assurance and process control. In a recent review [28] various nondestructive evaluation methods were discussed for application on surface coatings: electrical, magnetic, optical, and acoustic. Only those techniques based on acoustic properties showed sufficient promise for engineering applications.

Electron beam glazing has been applied in the course of the present research to develop modified metallurgical microstructures such as amorphous layers on crystalline substrates of PdCuSi, deposition of copper on 1 100 aluminium samples followed by electron beam melting in an attempt to form an aluminium-copper surface layer on the aluminium bulk, and formation of metastable martensitic microstructures on a pearlitic bulk of AISI 1045 steel.

Ultrasonic NDC of the thermally modified peripheral layer was determined by means of Rayleigh surface waves, using the device depicted in figure 5. The Rayleigh wave velocity is frequency independent. However, the extent of penetration of Rayleigh waves normal to the material surface is frequency dependent. Frequency analysis of the apparent Rayleigh velocities enables determination of the elastic properties of the layer, and the gauging of its average thickness. The Rayleigh surface wave velocity was measured by means of a wedge device (*fig.* 5) which converts longitudinal waves into Rayleigh waves, and vice versa. In the case of an amorphous PdCuSi layer, in which the Rayleigh surface wave velocity is about 20 percent smaller than the Rayleigh wave velocity in polycrystalline material, this technique was found to be particularly potent. Samples of 1053 carbon steel in the pearlitic state were electron beam heat treated to obtain a microstructurally modified surface layer of martensite. The Rayleigh velocity of the uniform pearlite was found to be higher by more than 2 percent than that of martensite. By measuring the Rayleigh wave velocity over a frequency range, thus varying the penetration depth of the Rayleigh surface waves, the modified layer depth could be nondestructively determined (*fig.* 6). The Rayleigh velocity remains constant as long as the Rayleigh waves probe a uniform material. When the Rayleigh waves, due to decreasing frequency or increasing wave length, begin to sample simultaneously both the modified martensite layer and the pearlite substrate, the measured Rayleigh velocity is expected to increase. This behavior is apparent in figure 6. The lower curve should increase and merge asymptotically into the upper curve (straight line) that exhibits the constant Rayleigh velocity in the pearlitic substrate. These measurements demonstrate the feasibility of the technique to nondestructively characterize the properties of

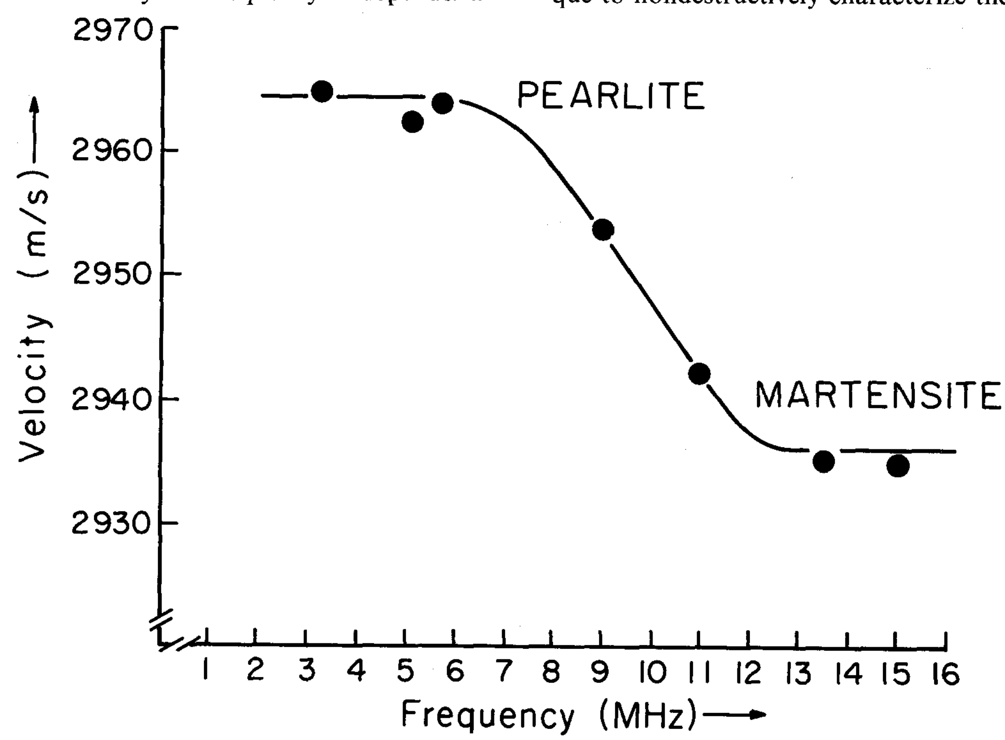

Fig. 6. — Variation of the apparent Rayleigh wave velocity with frequency (reciprocal of depth of penetration) in AISI 1045 steel. Regions of constant velocity (e. g., martensite) occur when the Rayleigh waves probe uniform layers of material.

a modified surface layer, and to evaluate its thickness. Preliminary studies have shown that the laser generation and laser-interferometric detection of Rayleigh surface waves can be applied for nondestructive, noncontact, evaluation of surface layers. Development of an in-process, real-time method would be of great technical importance.

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