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REMARKS ON IMPACT SHEARING

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ABSTRACT

A review is presented on recent progress in shear testing of materials at high and very high strain rates. Some experimental techniques are discussed which allow for materials testing in shear up to 10^6 l/s. More detailed informations are provided on experimental techniques based on the Modified Double Shear specimen loaded by direct impact. This technique has been applied so far to test a variety of materials, including construction, armor and inoxidable steels, and also aluminum alloys. The double shear configuration has also been applied to test sheet metals, mostly used in the automotive industry, in a wide range of strain rates. Details of both techniques, including measuring systems and elastic wave propagation in tubes, are discussed. In addition, a new experimental configuration which can be applied for experimental studies of adiabatic shear propagation and high speed machining is discussed.

The role of adiabatic heating at different rates of shearing is also discussed, including transition from pure isothermal to pure adiabatic deformation. It appears that the initial impact velocity is an important parameter in development of plastic localization.

Finally, a new development is discussed in determination of the Critical Impact Velocity in shear. A comparison is shown between recent experimental findings and a simple analytic estimation. The CIV in shear is a certain mode of adiabatic failure which occurs at relatively high shear velocities of adjacent material layers. Numerical simulations support the existence of the CIV in shear which can be recognized to some extent as a material constant.

Keywords: A. dynamics, B. metallic materials, B. stress waves, B. viscoplastic material, C. impact testing.

1. INTRODUCTION. GENERAL REMARKS ON FAST SHEARING

Shear is the fundamental mode of plastic deformation in materials. Testing of materials in shear over a wide range of strain rate and temperature can provide a fundamental knowledge in the development and improvement of constitutive relations used nowadays in large numerical codes. Advances in experimental techniques made it possible to determine plastic properties of materials in a wide range of strain rates, from 10^{-4} l/s to 10^6 l/s, that is nine decimal orders. However, when the nominal strain rate, that is the mean strain rate over the gauge length, is high enough, or time of plastic deformation is relatively short (order of hundred of ms and less), adiabatic instability and strain localisation can occur and dominate the process of plastic deformation. At still higher strain rates in shear (impact velocities ~ 100 m/s and higher) plastic waves in a deforming material can completely change the mechanics of deformation. In addition, at strain rates typically higher than $\sim 10^3$ l/s and above the so called threshold stress, the rate sensitivity of metals substantially increases. This phenomenon can be approximated by the pseudo-viscosity approach, for example Campbell and Fergusson (1970); Klepaczko (1988).

On the other hand, it is well known that experiments with strain rates higher than 10^3 1/s constitute a formidable task concerning technical difficulties, and only a limited number of reliable experimental techniques provide reliable results. Each setup configuration, that is specimen geometry and type of loading, offers some advantages and deficiencies in comparison to another one. Sometimes the roles may be completely inverted. It is then very important to test the same materials at high strain rates with different experimental techniques and compare the results.

Most studies of both constitutive modeling and adiabatic instabilities in shear, are based so far on results from the Split Hopkinson Torsion Bar technique (torsional Kolsky apparatus), (Duffy *et al.*, 1971, Lewis and Campbell, 1972). This experimental technique is quite reliable within a narrow range of strain rates, typically from 3×10^2 1/s to 2×10^3 1/s. A thin-walled tubular specimen of a short length, 2–5 mm, and wall thickness 0.5–1.0 mm, is loaded by the incident shear wave. The incident, reflected and transmitted torsional waves are analysed in a similar way as in the Split Hopkinson Pressure Bar (Kolsky, 1949, Lindholm, 1964, Klepaczko, 1971). The SHTB technique has been modified later to perform incremental/decremental strain rate tests (jump tests) (Frantz and Duffy, 1972). The thin-walled tubular specimens were used much earlier to test materials at different strain rates with specially designed torsion machines and also at impact shearing, typically up to 10^2 1/s, for example Klepaczko, 1965, 1967, 1969. The SHPB technique (original Kolsky apparatus) can also be used in shear by loading of specimens with special geometries. One such technique is the so called "hat" specimen, for example Hartman *et al.*, 1981, Beatty *et al.*, 1992. Because of a non-uniform deformation of the radial field within the shear zone in the "hat" specimen, determination of the shear stress vs shear strain is very difficult and needs an application of an FE technique. This technique is relatively well suited for a study of controlled initiation of Adiabatic Shear Bands (Beatty *et al.*, 1992).

A unique experimental technique is the pressure-shear plate configuration introduced by Clifton *et al.* for example Clifton and Klopp (1985). This technique represents an attractive configuration for studying dynamic plastic flow at shear strain rates from 10^5 1/s to 10^6 1/s. In this experiment, the strain rate of the order 10^5 1/s is achieved by sandwiching a very thin specimen between two hard elastic plates. The specimen is attached to the flyer and launched with the velocity of a few hundred m/s. The flyer impacts the stationary anvil in a vacuum at a small angle. Because of the inclined impact, the specimen is deformed in shear with a relatively high component of pressure. The elastic wave profiles, shear and normal components, which are transmitted by the specimen and the anvil plate, are recorded on the free external surface of the anvil. The wave analysis permits to find shear stress vs shear strain characteristics at strain rates in excess of 10^5 1/s. The characterisation of materials in shear at strain rates below 10^5 1/s must be complemented by a different experimental technique, for example SHTB. These two techniques are quite different, including the way of loading and specimen geometries.

Because of the effects of wave propagation in a specimen, every change of the specimen geometry and experimental technique introduces changes in the specimen response to fast or impact loading. The best solution is to use one specimen geometry for the widest possible spectrum of strain rates, for example from 10^{-4} l/s–10^{5} l/s or even 10^{6} l/s.

An effective specimen geometry which can be used in studies of dynamic plasticity at low, medium and high strain rates is the double-notch specimen. Such a specimen was first proposed by Fergusson *et al.* (1967), to study dynamic plasticity of single crystals. Later, the Double Shear specimen was applied, with the loading scheme consisting of the incident Hopkinson bar and transmitter Hopkinson tube by Campbell and Fergusson (1970), to study temperature and strain rate dependence of the yield stress of a mild steel. A very small gage length of 0.84 mm was used in the study mentioned above. Because of a small gage length of the original DS specimen, application of the conventional mass velocities occurring in the incident bar, from ~ 1.2 m/s to ~ 11 m/s in the work of Campbell and Fergusson, provided the nominal strain rates in shear up to $\sim 10^{4}$ l/s. Determination of higher shear strains from the DS specimen geometry, more than a few percent, by use of the method of the net displacement between the Hopkinson bar and Hopkinson tube (Campbell and Fergusson, 1970), leads to large errors due to a non-uniform shear and severe plastic deformation of the specimen supports. Some improvements, mainly to the DS specimen geometry, but with the gage length 0.8 mm, have been introduced later by Harding and Huddart (1979).

In order to study dynamic plasticity and adiabatic instabilities within a wide range of strain rates and at large strains, the concept of the double shear test has been completely modified to load specimens of the same geometry at very different velocities, from quasi-static to impact. This test technique is briefly discussed in the next part of this paper.

2. DIRECT-LOAD MODIFIED SHEAR TEST

This relatively new experimental technique was briefly described by Klepaczko (1991) and a more complete outline was given later (Klepaczko, 1994). It combines some advantages in comparison to the original DS technique developed by Fergusson *et al.* The fundamental change in comparison to the bar-tube configuration has been introduced by elimination of the incident bar and application of the direct impact by a projectile. Within the quasi-static region of strain rates, from 10^{-4} l/s up to ~ 500 l/s, a special rig was constructed to load specimens by a fast servo-hydraulic machine. On the other hand, the specimen geometry has been substantially modified, the shearing zones have been enlarged to 2.0 mm and the external parts enforced, to eliminate plastification of the support regions, the Modified Double Shear geometry is given elsewhere (Klepaczko, 1994). Because of the direct impact the risetime of the incident wave has been reduced to ~ 2 μs in comparison to ~ 30 μs in the bar-tube configuration. This experimental technique is shown schematically in Fig. 1. The flat-ended projectiles of different lengths made of maraging steel and of diameter $d_p = 10$ mm are launched from an air gun with desired velocity V_0; $1.0 < V_0 < 200$ m/s. Impact velocity is measured by three optic chains: source of light, photodiode and input/output optic fibers. Electric signals from the photodiodes are recorded by two time counters. The setup with three light axes makes it possible to determine

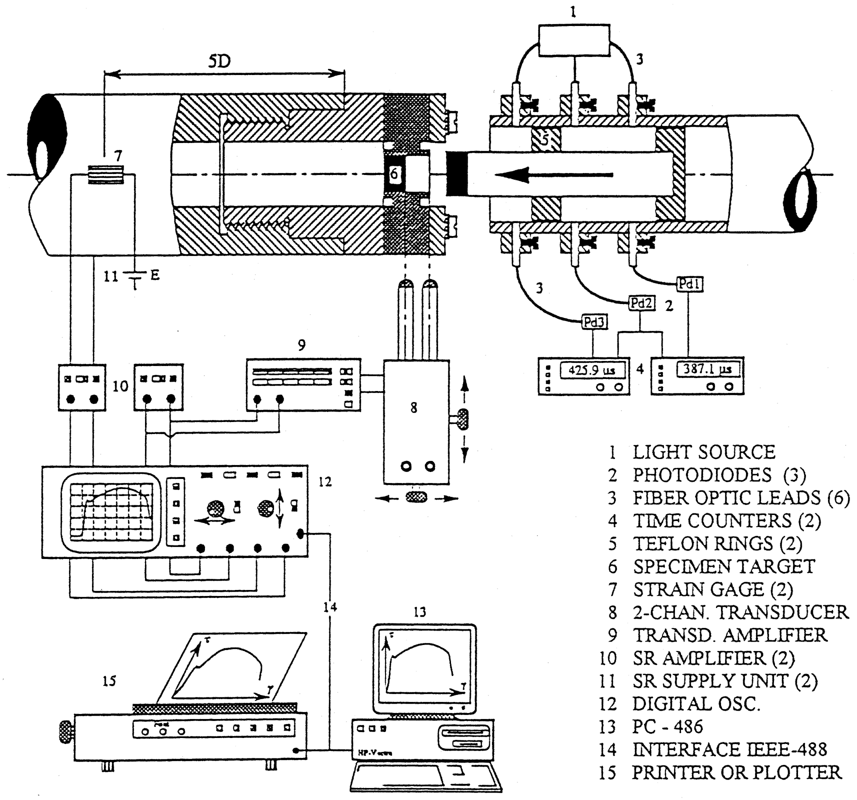


Fig. 1. Configuration of experimental setup for impact shearing of the MDS specimen (Klepaczko, 1991, 1994).

acceleration/decelaration of a projectile just before impact, so the exact value of V_0 at the impact face of the MDS specimen can be found. Axial displacement $\delta_A(t)$ of the central part of the specimen is measured as a function of time by an optical transducer, acting as a non-contact displacement gage. Since the double channel transducer is used, the second channel controls displacement $\delta_F(t)$ of the impact face of the MDS specimen. Measurements of V_0 and $\delta_F(t)$ make it possible to determine the coefficient of restitution for each test. A black and white target is cemented on the side of the MDS specimen (No. 6 in Fig. 1) and at the same time the impact end of the projectile is black ; in this way the non-contact displacement transducer also reacts to the movement of the impact face. The axial force transmitted by the specimen symmetric supports into the Hopkinson tube can be determined as a function of time, $F(t)$, from the transmitted longitudinal elastic wave $\varepsilon_t(t)$. The transmitted wave $\varepsilon_t(t)$ is measured by strain gages 7, DC supply units 11 and amplifier 10. All electric signals, that is voltages of displacements $\delta_A(\mathrm{T})$ and $\delta_F(t)$ and transmitted wave $\varepsilon_t(t)$ are recorded by the digital oscilloscope 12 and stored later in the PC hard disk for further analyses. After an analysis of recorded signals and elimination of time, a force-net displacement curve $F(\delta)$ can be constructed for each test and $\tau(\Gamma)$ and also $\dot{\Gamma}(\Gamma)$ characteristics determined, where τ is the shear stress, Γ strain, and $\dot{\Gamma} = d\Gamma/dt$ is the strain rate. The complete theory of the test is given elsewhere (Klepaczko 1994).

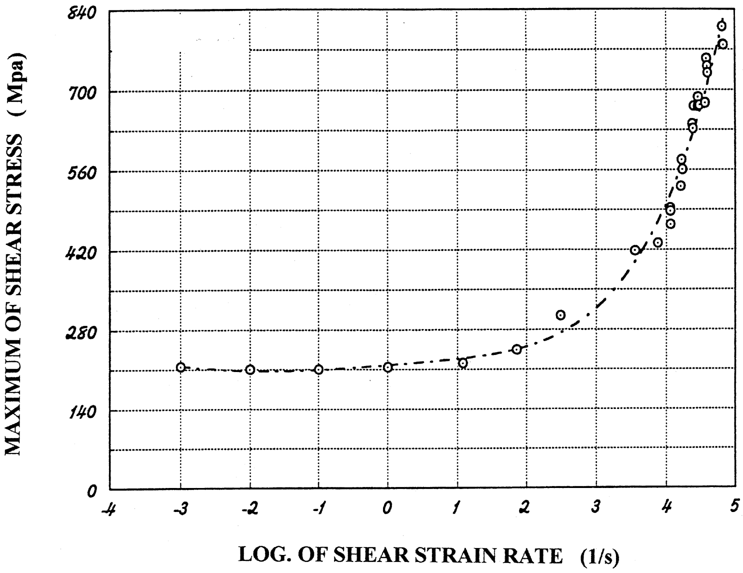
The experimental technique based on the direct impact on the MDS specimen has appeared to be quite effective and flexible in materials testing in shear at high strain rates, 10^3 1/s $< \dot{\Gamma} < 10^5$ 1/s. In addition, the special rig permits loading of the MDS specimen at low and medium strain rates, 10^{-4} 1/s $< \dot{\Gamma} < 5 \times 10^2$ 1/s. A fast, closed-loop hydraulic testing machine is used together with this device (Klepaczko, 1991). Thus, the experimental technique based on the MDS specimen assures a wide spectrum of the nominal strain rates, typically from 10^{-4} 1/s–10^5 1/s.

Several alloys, mostly varieties of steel, were tested by this method; almost all of them show a very high rate sensitivity above 10^3 1/s. One typical example is given in Fig. 2 (Klepaczko and Rezaig, 1994), where the maximum shear stress (Fig. 2(a)) and shear deformation at the final adiabatic localisation (Fig. 2(b)) is shown as a function of the logarithm of the shear strain rate in log [l/s] for a hot-rolled low alloy steel, 0.41% C, 5% Cr, 1.4% Mo. Above strain rate 10^3 1/s, a substantial increase of the maximum shear stress is observed. On the contrary, the adiabatic localisation strain increases initially, again up to $\sim 10^3$ 1/s and next, in excess of $\sim 2 \times 10^4$ 1/s, decreases rapidly. This is called the Critical Impact Velocity (CIV) in shear, which is discussed in the next part of this paper.

3. MACHINING BY DIRECT IMPACT

The idea of the direct impact on the MDS specimen has also been applied for high-speed machining. A new experimental setup has been put into operation in LPMM Metz which permits a ballistic high-speed machining up to ~ 100 m/s as well as for the testing of the dynamics of adiabatic shearing (Sutter *et al.*, 1997, Faure, 1996). The main modification lies in application of the projectile of a large diameter, $d = 50$ mm, guided without rotation in the air gun tube. The specimen to be cut is attached to the projectile and a pair of knives is fixed to the Hopkinson tube. The schematic picture of this arrangement is shown in Fig. 3. The specimen in the form of the parallelepiped, can be cut before testing with high precision to assure an exact chip thickness predetermined by the distance of two knives attached with sufficient precision to the Hopkinson tube. The length of cutting is predetermined by the length of the specimen, dimension L in Fig. 3. During the cutting process the mean force is transmitted by two knives into the Hopkinson tube in the form of the transmitted longitudinal elastic wave which is recorded by strain gages, signal conditioners, amplifiers and a digital oscilloscope. The whole scheme of the setup is shown in Fig. 4. The projectile mass can be adjusted according to the energy needed for an almost constant cutting speed and for the impact velocity. The typical range of cutting speeds is within the limits of 10 m/s–100 m/s. The impact velocity is determined in the same way as in the double shear technique: three sources of light S, fiber optics, three photodiodes PH and three time counters CT1 and CT2 (Klepaczko, 1994). The oscillograms obtained in the form of the transmitted wave as a function of time $\varepsilon_t(t)$ permit the force-projectile displacement characteristic to occur, with the assumption that the

(a)



(b)

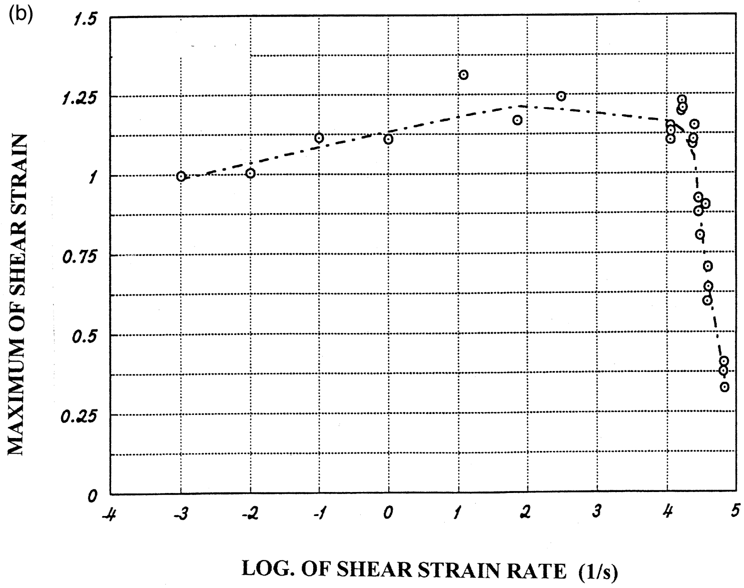


Fig. 2. Wide spectrum of shear strain rate for C-Cr-Mo hot-rolled steel; (a) Maximum shear stress vs log of shear strain rate (l/s); (b) Maximum shear strain of localisation vs log. of shear strain rate (l/s), (Klepaczko and Rezaig, 1995).

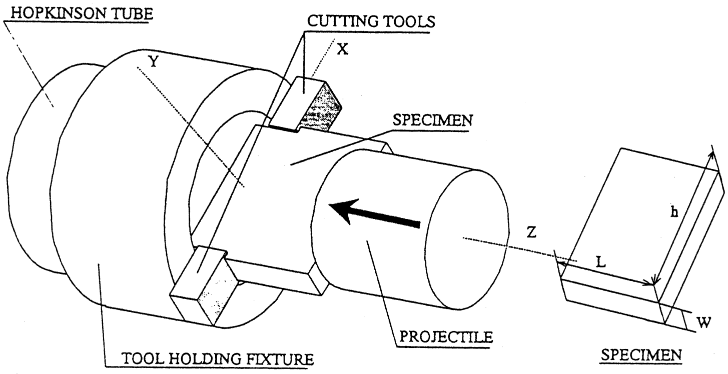


Fig. 3. Configuration of the specimen attachment to the projectile and tools fixed to the Hopkinson tube, projectile diameter 50 mm, (Sutter *et al.*, 1997).

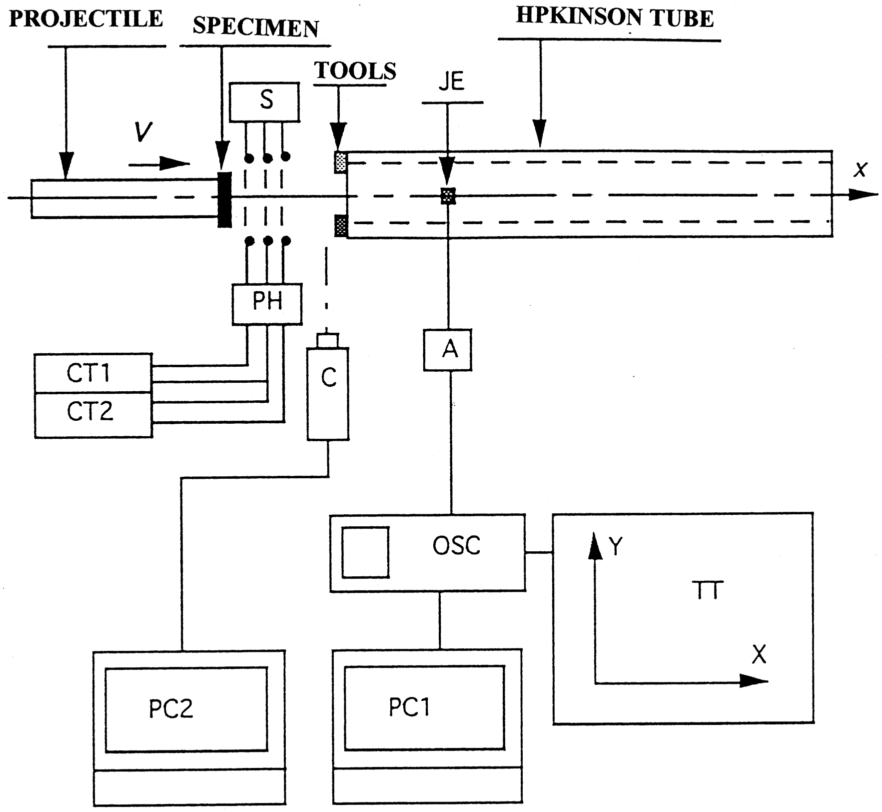
projectile deceleration is negligible. In general, the decrease of the velocity due to the cutting process was less than 4% (Sutter *et al.*, 1997). The theory of the test is practically the same as given by Klepaczko (1994).

Another recent application of the experimental setup shown in Fig. 4 was a study of the propagation of the adiabatic shear bands (Faure, 1996). The flat projectile made of a hard martensitic steel, and guided in the air gun tube, impacts a flat specimen attached to the Hopkinson tube. The scheme of loading is to some extent similar to that introduced by Kalthoff for Mode-II impact loading of cracks, for example Kalthoff (1990). The main difference is that in the LPMM setup, the force transmitted by the specimen supports can be determined from the transmitted elastic longitudinal wave measured in the Hopkinson tube. For instance, the mean crack velocity can be determined in this way. During crack propagation in Mode II, the force transmitted by the tube diminishes in proportion to the non-fracture ligaments in the specimens, and at the instant when the specimen breaks the force, it drops to zero. Because the initial length of the shear crack is known and the total time of the transmitted wave is measured, a mean crack speed can be determined, (Faure, 1996). It appears that in the case of a mild steel being tested, the mean crack speeds are not constant but increase with impact velocities.

In materials testing and machining at very different strain rates, additional effects like transition from isothermal to adiabatic deformation, adiabatic instability and localisation, and finally deformation wave trapping, complicate interpretation of the experimental results. Some of those features are addressed in the next part of this review.

4. ADIABATIC HEATING, INSTABILITY AND LOCALISATION

It is well known that during plastic deformation of materials, a large part of plastic work is converted into heat (Taylor and Quinney, 1934). When deformation is slow,



CT - TIME COUNTERS
PH - PHOTODIODES
S - LIGHT SOURCES
JE - STRAIN GAGES
A - AMPLIFIER
OSC - DIGITAL OSCILLOSCOPE
PC - COMPUTERS
TT - PLOTTER
C - SET OF 6 FAST CCD CAMERAS

Fig. 4. Configuration of experimental setup for impact machining, LPMM—Metz.

all heat generated is evacuated into surroundings by heat diffusion or by direct emission. However, when the process of deformation is short enough, there is no time for heat transfer and almost all plastic work is converted locally into volume heating. In a certain range of strain rates, the transition occurs between entirely isothermal and entirely adiabatic modes of plastic deformation. Some preliminary study on this subject was reported by Kaminski, 1976 and Litonski, 1985.

Because this transition depends, in the first place, on the geometry of the deformed body and also on the intensity of the heat extraction from the heated zones, a numerical analysis is very helpful in determining the region of strain rates and for which specimen geometry the transition occurs. When the thickness of deformed layer is $\sim$2.0 mm, like in the MDS specimen, the transition occurs at the following critical strain rates: copper $\sim$85 1/s, aluminum $\sim$68 1/s and a mild steel $\sim$48 1/s (Oussouaddi and Klepaczko, 1991). The finite difference technique has been applied, and the calculations were carried out at $T_0 = 300$ K, the initial temperature. The results support quantitatively the physical intuition that the critical strain rate increases in proportion to the thermal conductivity, which is the lowest for steel and the highest for copper. Since those values are based on the maximum temperature gradients, a complete transition into the entirely adiabatic conditions occurs at strain rates at least 5 1/s higher than the mean value. Variations in the specimen geometry also change the transition region, (Oussouaddi and Klepaczko, 1991).

Thermal softening during adiabatic heating leads directly to instability and localization, for example early works (Litonski, 1977, Rogers, 1979, Zener and Hollomon, 1944). In the case of pure shear, the condition for stability is reduced to maximum shear stress $d\tau = 0$, where τ is the shear stress (Litonski, 1977, Rogers, 1979). This condition can be rewritten into the form of zero tangent modulus $d\tau/d\Gamma = 0$ and $\Gamma = \Gamma_C$, the instability strain. A schematic stress-strain curve showing different stages of deformation during fast (adiabatic) shearing is shown in Fig. 5.

All stages shown in Fig. 5 were identified by high-speed photography during deformation of a tubular specimen made of HY-100 steel loaded in SHTB (Marchand and Duffy, 1988). During the first stage of deformation, that is, in between the yield point (τ_y, Γ_y) and the instability point (τ_C, Γ_C) where $d\tau/d\Gamma = 0$, strain distribution over the gage length is homogeneous. During stage 2, shown in Fig. 5, the strain distribution becomes inhomogeneous, and localization begins. Finally, during stage 3, localization occurs by catastrophic shear, the flow stress drops rapidly and the Adiabatic Shear Band is well formed. However, during this stage the high-speed

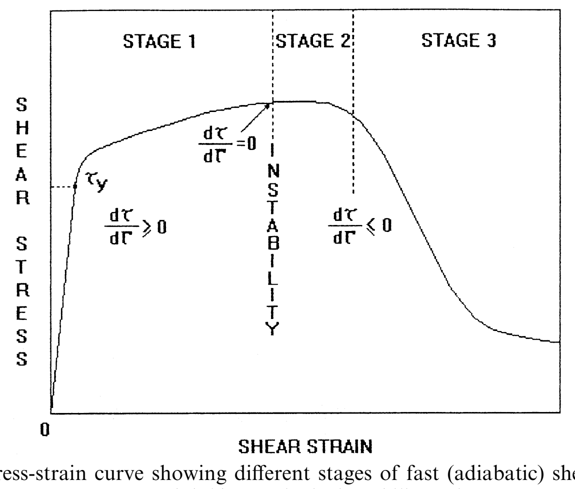


Fig. 5. Schematic stress-strain curve showing different stages of fast (adiabatic) shearing, τ_y is the yield stress and $d\tau/d\Gamma = 0$ is the instability point.

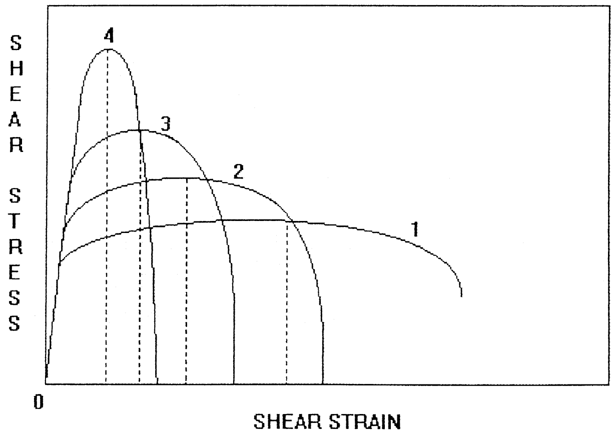


Fig. 6. Schematic evolution of stress-strain curves of industrial steels at strain rates higher than 5×10^2 1/s; (1) $\sim 5 \times 10^2$ 1/s; (2) $\sim 5 \times 10^3$ 1/s; (3) $\sim 1 \times 10^4$ 1/s; (4) $\sim 5 \times 10^4$ 1/s.

photography revealed some circumferential nonuniformities in formation of the ASB (Marchand and Duffy). The last part of stage 3 shows, which should be called stage 4, is typically observed for more ductile metals, a slowdown of the rate of the flow stress. Such behavior is caused by cooling of a very thin layer of material situated very close to the ASB (Litonski, 1985).

The instability point (τ_C, Γ_C) can be found for different constitutive relations, for example (Dormeval, 1987). A more general analysis of the condition $d\tau/d\Gamma = 0$ has been discussed by (Klepaczko, 1991, 1994b). Application of the condition for stability $d\tau/d\Gamma = 0$, and some form of equation for constitutive modeling, leads to the final result in the form $\Gamma_C(\dot{\Gamma}, T)$, when the adiabatic process of deformation is assumed together with a constant strain rate (Klepaczko, 1991). It has been found that an increase of flow stress when the strain rate is increased, has a negative effect on the onset of adiabatic instability, that is Γ_C is reduced when strain rate is increased (Klepaczko, 1994). The positive rate sensitivity increases production of plastic work converted into heat, this process accelerates formation of the instability, so the value of Γ_C is a diminishing function of the nominal strain rate. Several industrial steels tested so far in shear at strain rates from 10^{-3}–$\sim 10^5$ 1/s with the MDS method (Klepaczko, 1991, 1994a), showed a substantial evolution of the stress-strain curve. Schematic changes of the $\tau(\Gamma)$ curves observed for many industrial steels at increasing rates are shown in Fig. 6.

In this schematic Figure, the mean proportions are conserved to show the effect of the very high rate sensitivity on the yield stress and instability stress above $\sim 10^3$ 1/s. Contrary to the positive rate sensitivity of the critical stress τ_C, the critical strains of instability Γ_C always show a tendency to diminish when the strain rate is above $\sim 10^3$ 1/s. The same happens with the fracture strains. At very high strain rates this feature is even more abrupt; this occurs because of a superposition of the ASB formation and plastic waves in shear.

5. CRITICAL IMPACT VELOCITY IN PLASTIC SHEARING

It has been shown recently (Klepaczko, 1994b, 1995), that during shear deformation imposed by a high-velocity, plastic waves excited in a deformed material can completely change the mechanics of plastic field. As a rule, an intense plastic deformation will appear near the impact end of a specimen. For the MDS specimen with the gage length 2.0 mm, the nominal strain rate when the plastic waves start to dominate is 5×10^4 l/s, that is, the velocity of shearing reaches value ~ 100 m/s.

Since formulation of the rate independent theory of elasto-plastic waves in solids by Kàrman, Taylor and Rakhmatulin, in the late forties and early fifties (for a review, see Cristescu, 1967), it is known that the longitudinal plastic deformation can be localised in thin bars by a high velocity impact (Kàrman and Duvez, 1950). This deformation trapping by longitudinal plastic waves is called the Critical Impact Velocity in tension (Kàrman and Duvez, 1950, Klepaczko, 1968). It has been shown recently that the Critical Impact Velocity in shear can be determined experimentally using the MDS specimen and the direct impact loading, (Klepaczko, 1994b, 1995). This is demonstrated in Fig. 2(b), where a systematic drop in the critical strain of shear localisation is observed for a low alloy steel around impact velocity 100 m/s. An existence of the CIV in shear was predicted by a numerical method by Wu and Freund (1984).

A more detailed analytic study was published elsewhere (Klepaczko, 1995); here, only a brief discussion is offered. It is clear that the CIV in shear is closely related with adiabatic heating and thermal softening. The CIV in shear is caused by an instantaneous instability and strain localisation superimposed on plastic wave propagation in shear. The rate-independent wave propagation theory has been applied to analyse CIV in shear and the final formula was derived by Klepaczko (1995).

Preliminary numerical estimation of the CIV values for 1018 steel (French Standard XC18) have confirmed the usefulness of the analytic procedure proposed by Klepaczko (1994b, 1995). The value of CIV obtained with a simplified constitutive relation was $V_{cr} = 98.0$ m/s and $\Gamma_C = 4.9 \times 10^4$ l/s for 2.0 mm gage length, the value very close to the one determined by the MDS direct impact technique, $V_{cr} \cong 90$ m/s. The experimental technique based on the MDS specimen and direct impact has been applied so far for determination of the CIV for three steels. Besides XC18 mild steel, the CIV determined for VAR 4340 steel (52 HRC) was $\cong 130$ m/s and in the case of hot-rolled C-Cr-Mo steel $\cong 100$ m/s.

Of course, the process of adiabatic shearing and localisation superimposed on the propagation of plastic waves leads to shear fracture. It is interesting to note that the superposition of those two processes leads to a substantial decrease of the energy to fracture. Such behavior of the MDS specimen is demonstrated for C-Cr-Mo hot-rolled steel in Fig. 7. The total energy to fracture normalised by the specimen cross section is plotted vs logarithm of shear strain rate in l/s. Up to values of the nominal strain rate $\sim 1.5 \times 10^4$ l/s, the energy slightly increases up to 0.87 J/mm^2, but above this value a substantial drop is observed, up to 0.4 J/mm^2 at strain rate $\sim 7 \times 10^4$ l/s ($V_{cr} = 134$ m/s).

The phenomenon of the CIV in shear has been studied by FE technique for VAR 4340 steel, ~ 50 HRC (Klosak and Klepaczko, 1997). An infinite layer with a small

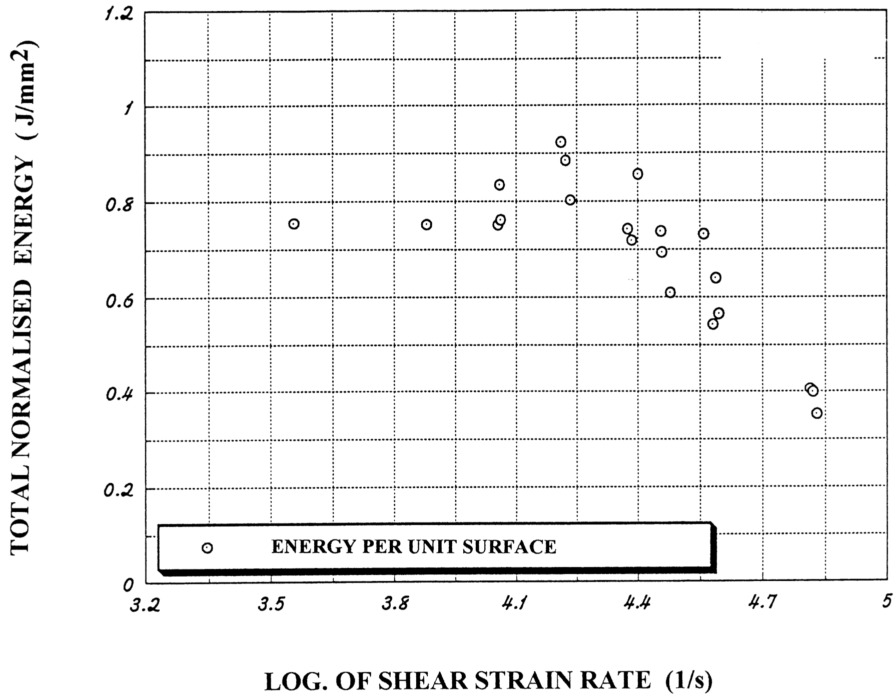


Fig. 7. Total fracture energy of the MDS specimen vs log of the nominal strain rate in shear (l/s); C-Cr-Mo hot-rolled steel (Klepaczko and Rezaig, 1995).

geometrical imperfection was analysed. Seventeen loading velocities of the MDS specimen were assumed, and for each velocity the instability shear strain ($d\tau = 0$) and the deep localisation strain have been found. The final results are shown in Fig. 8. Both characteristic strains are shown as a function of the different velocities, from quasi-static to impact, 160 m/s. Those detailed calculations entirely support experimental observations discussed in the preceding parts of this paper. In between impact velocities from 105 m/s to around 130 m/s, a CIV transition occurs. The analytic approximation of the CIV in shear for this steel yielded a value of 114 m/s. However, the numerical study clearly indicates that the CIV phenomenon is a process. The fracture energies for the VAR 4340 steel (the MDS geometry) have been estimated as a function of the impact velocity by integration of the force-displacement curves found by the FE technique. The final result is shown in Fig. 9. At lower impact velocities, the energy to the final localisation increases up to 681 MJ/m^3; however, at impact velocities higher than 100 m/s, the energy drops considerably, to the value of $\sim$8.0 MJ/m^3. Thus, the energy drop is slightly less than a hundred times. The striking similarity can be instantly spotted between the experimental results of Fig. 7 and the numerical results shown in Fig. 9. It is clear that the CIV in shear can be understood as a new material constant. More precise experiments could be performed to determine this value for different materials.

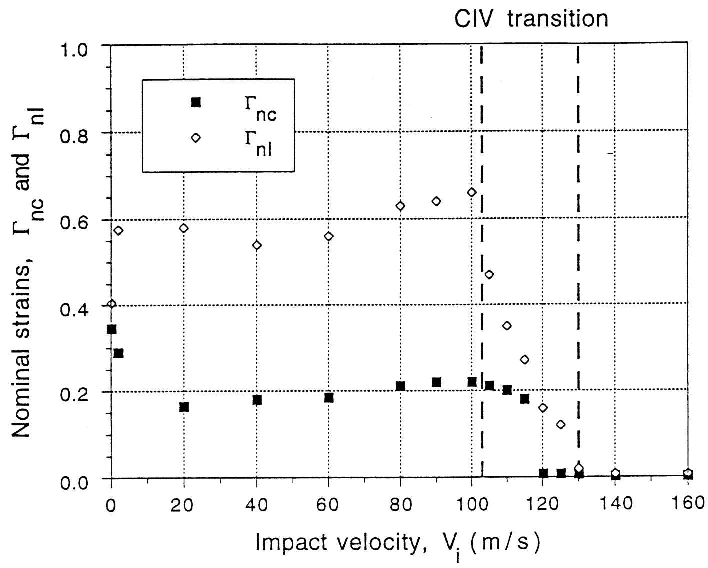


Fig. 8. Results of numerical calculations by FE method for VAR 4340 steel. Nominal shear strains of instability Γ_{nc} and localisation Γ_{nl} vs impact velocity; CIV indicates the Critical Impact Velocity transition, (Klosak and Klepaczko, 1997).

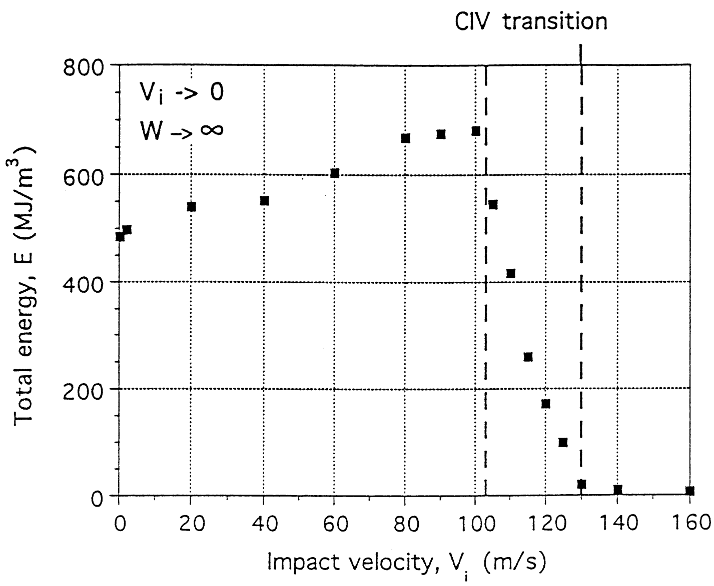


Fig. 9. Results of numerical calculations by FE method for VAR 4340 steel. Total energy to advanced localisation vs impact velocity; CIV indicates the Critical Impact Velocity transition (Klepaczko, 1996).

6. DISCUSSION AND CONCLUSIONS

It has been shown in this review that materials testing in shear within a wide range of strain rates, from quasi-static to impact and up to 10^5 l/s, is possible using the MDS specimen loaded at moderate rates or by a direct impact. Since the duration of experiments occurs at very different time spans, additional effects like transition from isothermal to adiabatic deformation, adiabatic instability and localisation, and finally CIV in shear, change the deformation process. In each range of strain rates, different processes may dominate. Indeed, the thermal coupling associated with heat production due to plastic deformation and heat conduction plays an important role in dynamic plasticity during shearing. Characteristic values of the CIV in shear can be proposed as a new material constant. The FE numerical technique has confirmed quantitatively and qualitatively existence of the CIV in shear. Analytic methods to estimate the value of the CIV in shear may be used as a first approximation. Of course, a value found will depend on the quality of the constitutive relations used.

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