Acta metall. mater Vol 39, No 4, pp 719–724, 1991
Printed in Great Britain

0956-7151/91 $3 00 + 0 00

EXPERIMENTAL INVESTIGATION OF SURFACE INSTABILITIES IN CYLINDRICAL TENSILE METALLIC SPECIMENS

D. RITTEL†, R. AHARONOV, G. FEIGIN and I. ROMAN

The Hebrew University of Jerusalem, Graduate School of Applied Science and Technology, Applied Physics and Materials Science Department, Jerusalem 91904, Israel

(Received 23 December 1989; received for publication 19 September 1990)

Abstract—The orange peel phenomenon which is characteristic of deformed coarse-grained materials is examined in order to supplement continuum theories of surface instabilities with microstructure related parameters Specifically, the relationship between microstructure and wavelength of the surface instabilities is investigated The approach is experimental and consists of spectral analysis of surface undulations in tensile cylindrical specimens The results indicate that the fundamental wavelength of the phenomenon equals a certain number of average grain diameters and is therefore related to the grain size, but also probably to material hardening characteristics The results also show that the longitudinal mode of undulation is predominant and induces the circumferential mode, suggesting that despite a lack of axial symmetry, an analytical solution of the longitudinal modes can accurately describe the physical picture However, it is felt that additional research work is needed on both the experimental and theoretical levels in order to provide a deeper understanding of the phenomenon

Résumé—On étudie le phénomène de la peau d'orange, qui caractérise les matériaux déformés à gros grains, afin de compléter les théories de milieu continu des instabilités superficielles par les paramètres microstructuraux concernés. On étudie plus particulièrement la relation entre microstructure et longueur d'onde des instabilités de surface Il s'agit d'une approche expérimentale qui consiste à réaliser une analyse spectrale des ondulations de surface sur des éprouvettes de traction cylindriques La longueur d'onde fondamentale du phénomène est égale à un certain nombre de diamètres moyens des grains; elle dépend donc de la taille des grains, mais aussi probablement des caractéristiques du durcissement du matériau Le mode longitudinal d'une ondulation est prépondérant et induit le mode circonférentiel, ce qui suggère que, bien qu-il n'y ait pas de symétrie axiale, une solution analytique des modes longitudinaux peut décrire de façon précise le phénomène physique On pense cependent que des recherches supplémentaires, tant expérimentales que théoriques, sont nécessaires pour une meilleure compréhension du phénomène

Zusammenfassung—Die Orangenschalenstruktur, typisch für verformte grobkörnige Materialien, wird untersucht, um die Kontinuumstheorien der Oberflächeninstabilitäten mit mikrostrukturverwandten Parametern zu ergänzen Insbesondere wird der Zusammenhang zwischen der Mikrostruktur und der Länge der Oberflächeninstabilitäten untersucht Diese Näherung ist experimenteller Natur und besteht in der Spektralanalyse der Oberflächenriffel an einer zylindrischen Zugprobe Der Ergebnisse weisen darauf hin, daß die Grundwellenlänge einer gewissen Zahl von Korndurchmessern entspricht und daher mit der Korngröße zusammenhängt, aber möglicherweise auch mit den Eigenschaften der Verfestigung des Materials. Außerdem zeigen die Ergebnisse, daß die longitudinale Mode bei den Riffeln vorwiegt, die eine Mode auf dem Umfang induziert; das weist darauf hin, daß eine analytische Lösung der longitudinalen Moden trotz der verletzten Achsailsymmetrie ein physikalisches Bild ergibt Allerdings scheint wohl weitere experimentelle und theoretische Arbeit nötig, um die Erscheinung tiefer zu verstehen

INTRODUCTION

Surface instabilities which develop during deformation of a solid have been extensively studied in the last decade. These instabilities are considered as a special case of bifurcation of the plastic deformation into surface modes Hill and Hutchinson [1] studied the problem of a rectangular block subjected to a plane strain deformation while Bassani *et al.* [2] solved the problem of a spherical hole with uniform remote axial tension or compression. Hutchinson and Tvergaard [3] studied surface instabilities while making use of different theories of plasticity Their study along with that of Bassani *et al.* [2] showed that the prediction of surface instabilities is strongly dependent on the type of plasticity theory employed (i.e the so called deformation theories can successfully predict the occurrence of surface modes whereas this is not the case with flow theories) In the context of axi-symmetric specimens, Hutchinson and Miles [4] who

†Present address: Laboratoire de Mécanique des Solides (U A CNRS 317), Ecole Polytechnique, 91128 Palaiseau Cedex, France

studied the case of a tensile cylinder could not foresee surface modes since they used a flow theory of plasticity. While these studies can predict the occurrence of surface instabilities, they do not deal with their development. This issue was addressed by Hutchinson and Obrecht [5] who assumed the wavelength of the initial nonuniformity and studied its evolution in creeping materials. The above mentioned literature is based on a continuum mechanics approach so that microstructural concepts such as metal grain size do not explicitly appear in these models. However, both Hutchinson and Tvergaard [3], and Bassani *et al.* [2] reached the conclusion that the phenomenon must be related to the grain size (through its wavelength) and that "the scale of the surface bifurcations found here is determined by grain size considerations". Indeed, when experimental evidence is brought to support theoretical predictions, it becomes quite evident that microstructural parameters play an important role in the development of surface instabilities. Such observations can be found in several experimental studies, e.g. Hahn and Rosenfield [6], Onyewuenyi and Hirth [8]. Recently, Rittel and Roman [8] investigated the deformation of coarse-grained (≈ 1 mm) cast Hadfield steels, and one of their conclusions was that the development of noticeable surface rumpling (also called "orange peel") with proceeding plastic deformation belongs to the class of surface instabilities mentioned above. However, the undulations were qualified of "coarse" or "fine" on a visual qualitative basis only.

Consequently, the purpose of this study is to present a detailed characterization of the orange peel phenomenon with the following issues being addressed:

—coarse vs fine orange peel,
—relationship between the wavelength of surface instabilities and the grain size,
—axisymmetric nature of the surface instabilities in initially axisymmetric specimens,
—relationship between longitudinal and transverse modes of undulation.

EXPERIMENTAL

Cylindrical (8 mm in diameter) tensile specimens of commercial aluminum, aluminum alloy 6061-T651 and cast Hadfield steel were used in this study. The specimens were carefully prepared in order to minimize surface defects and the formation of an external hardened layer. They were subsequently strained to rupture. Longitudinal and transverse metallographic sections (profiles) of deformed and undeformed samples were polished and etched by standard techniques. Material grain size, which was determined by the lineal intercept method [9], is shown in Table 1. The extent of the surface undulations was digitally characterized by measuring, at equidistant intervals, the distance between the specimen surface and an arbitrary reference line connecting the specimen's ends (longitudinal) and a reference circle (transverse) respectively, on metallographic sections. Experimental details of the digitization process are given in Table 2. The digitized profile was then filtered by means of hanning window [10] in order to minimize the influence of the specimen's edges on the spectral decomposition. Filtered data were next fed into a Fast Fourier Transform (FFT) routine for power spectrum determination, that is the contribution (weight) of each spatial frequency to the overall pattern.

Table 1. Average grains size of the undeformed investigated materials

Material	Average grain diameter (mm)	Standard deviation (mm)
Commercial Al	0.60	0.37
Al 6061-T651	0.64	0.41
Cast Hadfield Steel	0.98	0.48

RESULTS

Figure 1 shows two fractured specimens of Hadfield steel. One is made of "fine-grained" material (average diameter 200 microns), whereas the other specimen is made of coarse-grained material (average diameter 1 mm). From this figure, it is evident that the fine-grained specimen exhibits surface undulations of much finer appearance. Examination of the cross section of the specimens reveals that the fine-grained specimen keeps a nearly circular shape whereas the other specimen tends markedly towards ovalization. Additional tensile specimens made of different materials exhibiting heavy surface rumpling (along with the specimens of this study) are shown in Fig. 2.

Figure 3 shows longitudinal and transverse metallographic sections of the different specimens used in this study. It is immediately evident that some information about the undulations is lost in the 2-D views as compared with 3-D views of Fig. 1. Dense undulation patterns which were perceived on the surface of the specimen are no longer observable on metallographic sections and only long wavelength patterns are noticeable. In one of the sections, we have outlined the grain boundaries in order to emphasize the individual contribution of surface grains to the overall pattern.

Table 2. Experimental details of the digitization technique. L and T stand for longitudinal and transverse section respectively. OP3 and OP4 were taken from the same sample

Sample	Type	Material	No. of steps	Unit interval size (mm)
OP1	L	Comm. Al	128	0.064
OP2	T	Al 6061	128	0.040
OP3*	T	Hadfield	64	0.294
OP4*	L	Hadfield	64	0.323
OP5	T	Al 6061	128	0.040
OP6	L	Hadfield	256	0.176

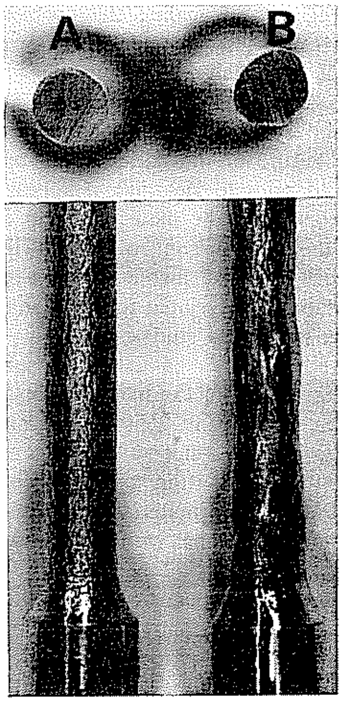

Fig. 1. Fractured specimens of cast Hadfield steel. A is made of fine-grained material with respect to B, the specimens being otherwise identical. Note the coarser surface undulations in B and macroscopic ovalization of its cross section.

The various power spectra obtained from the Fourier transform of the digitized profiles are shown in Fig. 4. On these plots, the frequency domain corresponding to the average grain diameter has been delimited and marked by G. Such limits were determined to be around half a grain diameter, corresponding to one standard deviation of the measurements. In addition, the energy scale has been normalized with respect to the second frequency.

Examination of the power spectra reveals first of all that most of the energy is concentrated in the low spatial frequencies and the energy corresponding to the higher frequencies tends to lie in the background noise. Furthermore, there is a general tendency for energy to decrease with increasing frequency and no dominant peak is observed in the central range of frequencies. Consequently, a "most probable fundamental frequency was identified (in the low frequency range) by noting its higher order harmonics. These harmonics are listed in Table 3, and the fundamental frequency is converted to an equivalent number of average grains. The results shown in Table 3 indicate that the dominant spatial frequency is dictated by a number of grains rather than by a single grain. For the various aluminum alloys, the dominant wavelength of the surface undulations does not exceed 3 average grains, whereas it reaches about 8 grains for Hadfield steel.

Table 3. Selected frequencies from power spectra of the investigated samples. These frequencies are most probable harmonics of the fundamental frequency listed in the table. The right handside column is the equivalent number of average grains corresponding to the fundamental wavelength

Sample	Frequency number	Fundamental frequency	Equivalent number of average grains
OP1	7 14 21	7	1.9
OP2	3 5 7 12 15 19 23	3–4	2.0–2.6
OP3	3 5 7 19	3–4	4.7–6.3
OP4	4 6 9 12 15	3–4	5.2–6.9
OP5	5 10 13 19	5–6	1.3–1.6
OP6	5–6 12	6	7.6

DISCUSSION

Visual examination of orange peel on two specimens of Hadfield steels shows that the surface roughness is directly related to the grain size of the material in the sense that coarser grained material yields a coarser undulation pattern. Although this observation confirms previous qualitative observations, the question of the quantitative relationship still needs to be answered and it seems that the numerical technique employed here is an original and accurate means of addressing this issue. But it should be emphasized that, whereas the roughness of surface undulations is dictated by both the wavelength and

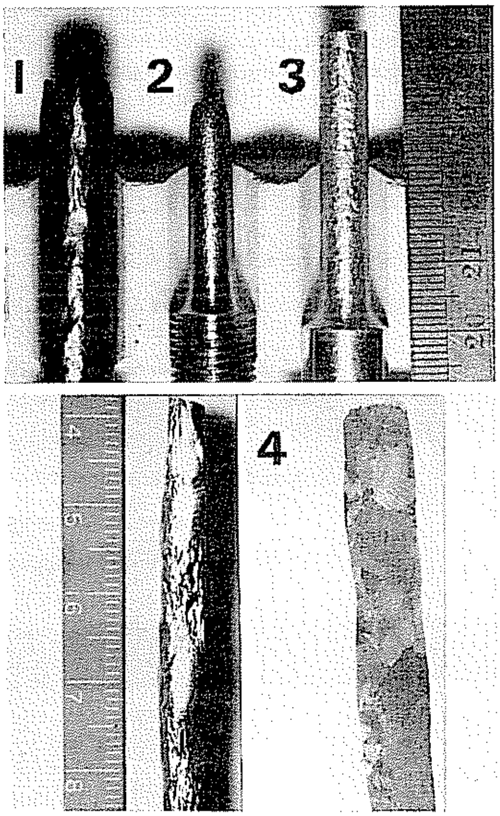

Fig. 2. General appearance of the orange-peel phenomenon in various materials: 1. commercial brass; 2. 304 Stainless steel; 3. commercial aluminum (employed in this study); 4. cast Hadfield steel (employed in this study) and its longitudinal profile.

the local amplitude of the phenomenon, the present work deals with wavelength considerations only.

The results show that the fundamental frequency of the surface undulations corresponds to a wavelength of a few average grains and the finer pattern is due to harmonics of this frequency. Here we recall Hutchinson and Tvergaard's results on commercial aluminum [3]: their visual observations showed that, superimposed on a fine pattern of about one grain size, longer wavelength patterns ranging from 2 to 8 grains were observed according to the material grain size. Our results are similar to theirs in the sense that our coarse grained aluminum exhibits a relatively short wavelength pattern. But, even if it may appear from these results that the main wavelength increases with decreasing grain size of a given material, one must keep in mind that visual observations reported by these researchers are not sufficient to draw a firm conclusion. Furthermore, when comparing two different materials (aluminum and Hadfield steel), it must be recalled that these materials are fundamentally different in their mechanical properties (Young's modulus, yield strength and hardening properties). The observations of longer fundamental wavelength in Hadfield steel correspond to the following qualitative fact; while an aluminum surface grain is relatively independent of its neighbors in the sense of long range influences, this is not the case for Hadfield steel for which displacements in a given surface grain are also experienced by its long range neighbors. Division of the main wavelength by the average grain size is a convenient way of scaling the problem: should surface waves be independent of the properties of the material on which they occur, the above ratio should be identical for all materials. This is not the case and since the phenomenon is related to the plastic nature of the material (no orange peel was observed prior to yielding), it appears that the relevant property is the material strain hardening. However, this assumption requires further experimental work and meanwhile, the wavelength of surface instabilities is related to the geometry of the specimen in theoretical studies.

The next subject to be discussed concerns the axisymmetric nature of the phenomenon in initially axisymmetric specimens. Visual examination of deformed specimens is not sufficient to answer this problem, but examination of transverse profiles shows that for a given material, the phenomenon is not axisymmetric and that with increasing grain size, the degree of symmetry decreases as the transverse profile tends towards macroscopic ovalization. Both the longitudinal and circumferential mode of undulation contribute to the phenomenon and it is interesting to know whether these modes are related in some way. Power spectra obtained for longitudinal and transverse sections of the same specimen show that both sections are characterized by nearly similar spectral components, thus surface undulations appear to be of identical nature in both directions. This finding is not surprizing if it is understood that the development of surface waves is a simple natural way

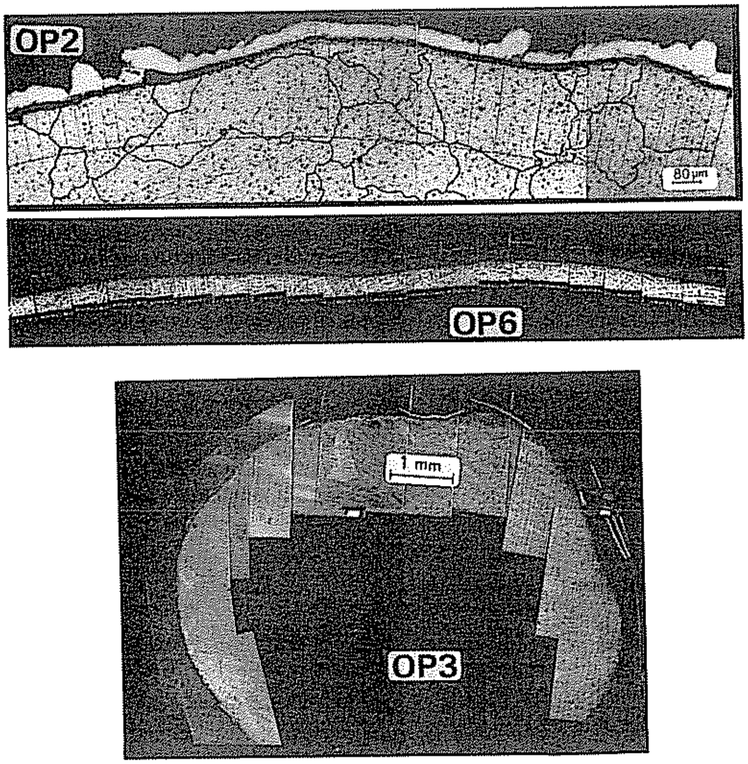

Fig. 3 Typical longitudinal (OP6) and transverse (partial OP2 and OP3) metallographic profiles. Grain boundaries and digitization marks have been outlined in OP2. All specimens were nickel plated.

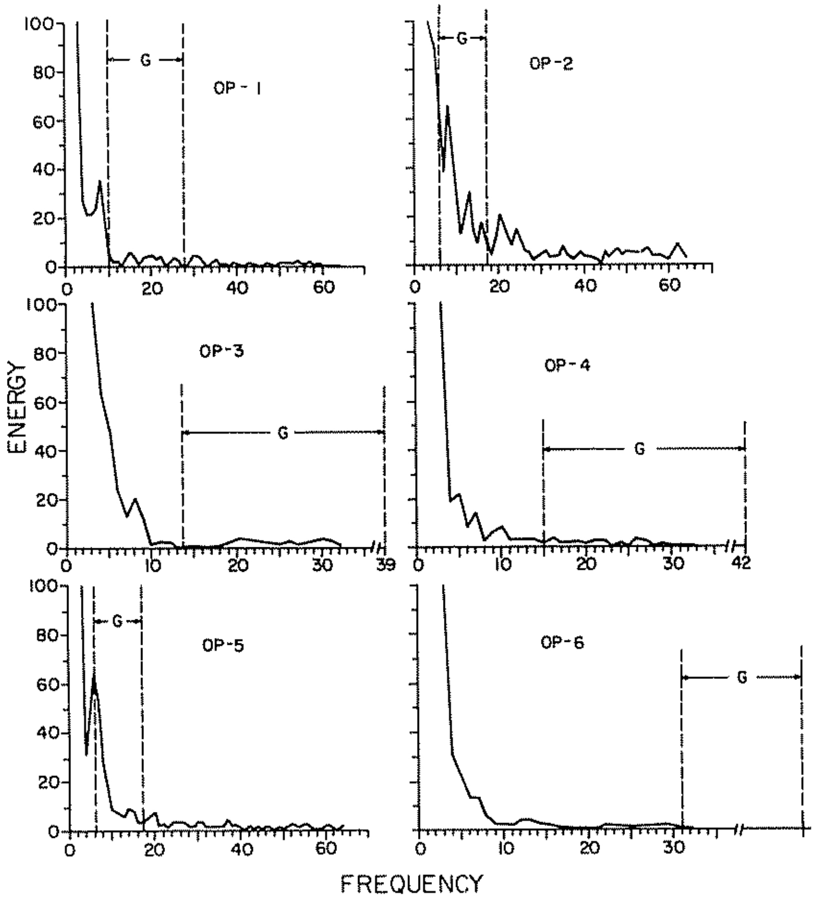

Fig 4 Typical spectra (energy in arbitrary units vs spatial frequency) of the investigated specimens DC value is the first point ($N = 1$, not plotted) so that point N corresponds to frequency $N - 1$ Energy range has been normalized with respect to the second frequency The domain of frequencies corresponding to the average grain diameter, $G \pm 1/2G$ is marked by the dashed lines.

of achieving high surface strains by increasing the average length of a surface element with respect to a parallel internal element This state of high surface strains following bifurcation has been predicted numerically by Hutchinson and Tvergaard [3] and measured in cast Hadfield steel by Rittel and Roman [8]. The same argument regarding longitudinal undulations applies to the circumferential direction since both directions are related by volume preservation requirements. In other words, once longitudinal waves form and induce high strains on a thin surface layer, these waves must also form on the circumference in order to preserve the volume of this layer. Furthermore, since the longitudinal pattern does not depend on the angular orientation of the section, one does not expect the circumferential pattern to vary with location of the transverse section across the specimen's gagelength. Consequently, it appears sufficient to treat the longitudinal mode as predominant so that it induces the circumferential mode This hypothesis is further supported by the fact that when cracking is associated with a surface layer, the orientation of the surface cracks is nearly perpendicular to the longitudinal direction, which is also the tensile axis (see e.g. Hutchinson and Tvergaard [3], Rittel and Roman [11]) This finding can be applied in the sense that even if assumptions of axial symmetry are not fully justified (and in the absence of analytical solution to the cylindrical problem), it appears that an analytical solution of the longitudinal modes will provide sufficient information on the overall phenomenon.

The last point to be addressed concerns the so called long vs short wavelengths which characterize surface instabilities as well as their depth of decay. In the continuum approach, the concept of long vs short wavelength is not further defined since material microstructure is not of concern. The present results show that a length corresponding to 8 coarse grains of Hadfield steel can represent the undulation. Such imperfection is definitely not short with respect to the specimen's radius but it is still short relative to its length, when phenomena such as necking are considered. It is therefore suggested that the term long wavelength be kept for lengths corresponding to the specimen's length itself. Furthermore, surface waves are expected to decay exponentially from the surface of the specimen in a distance corresponding to their wavelength. Even if this applies to a semi-infinite solid rather than a finite tensile specimen, the results obtained for Hadfield steel would mean a depth of decay of the order of the specimen radius which definitely does not characterize surface waves. Thus, it appears reasonable to assume that the depth of decay of surface waves is related essentially to their amplitude which is in turn related to the average grain size.

As a final remark, many questions remain unanswered and it is felt that additional work is required to deepen our understanding of the phenomenon; namely a bifurcation analysis of cylindrical tensile specimen with the introduction (if possible) of a physical length scale governing the surface modes [12]. In addition, a better understanding of the physics of the deformation of free surfaces is expected to yield a better comprehension of the relationship between surface and bulk deformations.

CONCLUSIONS

The following conclusions can be drawn from the present study:

—The fundamental wavelength of the orange peel phenomenon, as a case of surface instability, is equal to the size of a number of average grain diameters rather than to a single grain.

—The fundamental wavelength is not only dictated by geometrical or grain size considerations, but also probably by the material strain hardening characteristics.

—Longitudinal and circumferential undulations yield very similar spectral patterns. Despite a lack of axial symmetry, it appears sufficient to solve the problem of the longitudinal undulations since circumferential undulations stem from the former.

—The term "short wavelength" should apply to any length which is smaller than the specimen gagelength with no further restrictions.

—Additional research work is still needed on both the experimental and theoretical levels in order to provide a deeper understanding of the phenomenon.

Acknowledgements—The authors would like to acknowledge J. W. Hutchinson for his interest in the work. One of us (D. R.) is indebted to D. Durban and E. T. Onat for useful discussions.

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